APPENDIX B

ARSYNCO, INC.

HYDROGEOLOGIC CONCEPTUAL SITE MODEL

2014

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HYDROGEOLOGIC CONCEPTUAL SITE MODEL
ARSYNCO, INC.
(JMC, 2003 & JMC, 2013)

1.0 HYDROGEOLOGY

1.1 Surface Drainage

The Arsynco site lies within the Hackensack River Basin. Thus, the Hackensack River and its tributary streams are the primary discharge points for regional surface drainage.

The long, straight Berry's Creek Canal was not present at the end of the 19th century (Wilson 1901, see Figure C-1). The canal runs northwest-southeast, from Berry's Creek to the Hackensack River, parallel to and just south of the current location of New Jersey State Highway #3. The canal cuts off approximately the lower one third of the historical channel of Berry's Creek. Construction of this canal, along with historic and continued filling and development of the surrounding marsh areas, may have amplified the magnitude of tidal influences on ground water at the Arsynco site over the past 80 to 100 years. These factors shortened the stream-flow path up to the site and reduced the number of distributary tidal channels available to accept tidal flow downstream from the site. Tidal influences on ground water flow at the Arsynco site are significant and are discussed below.

Cook et al. (1884, Figure C-2) show that area of the Arsynco site as marshland but do not show any tidal drainage ditches in the vicinity of the site in 1884, although they do indicate the presence of Broad Street and Division Avenue extending southeast to the current location of 20th Street (see Figure C-2). Smock and Vermeule (1896, Figure C-3) and Wilson (1901, Figure C-1) indicate the presence of a lattice of artificial (i.e., man made) tidal drainage ditches on their topographic maps. The consistency of the Smock and Vermeule (1896) and Wilson (1901) maps, along with the drainage ditch details, supports the suggestion that Cook et al. (1884) may have mapped *planned* development east of the railroad rather than actual streets existing at that time.

The regional pattern of surface runoff near the Arsynco site is toward the east and southeast based on the topographic profiles shown in Figure C-2. The topographic highs and their covering with glacial till (Figure C-2) support this conclusion. The urban character of the area will accentuate this surface runoff.

Existing, tidal drainage ditches currently run along (or near) the eastern, southern, and western boundaries of the site, and empty into Berry's Creek (via Never Touch Creek). Historic aerial photographs indicate that an east-west trending tidal drainage ditch system also formerly extended to the north of the site until at least 1966, in the area that is now the rear driveway to the Northern Eagle Beverage property and along the border with the adjacent Henkel (Diamond Shamrock) property. The magnitude of tidal fluctuations in these ditches is not accurately known. Estimates of the tidal range are from 3 to 4.5 feet based on rough measurements made during Arsynco site visits on December 3 and 4, 2002. These ditches are a discharge point for the shallow ground water flowing to the south and east on the site. The ditches are also a discharge point for shallow groundwater flowing from other properties surrounding the Arsynco site (e.g., Cosan Chemical, East Coast Toyota Service Center, etc.). The ditch located to the west of the site runs from north to south and is located on the opposite side of the train tracks. This ditch, which extends along the tracks long distances north of the Arsynco site, connects directly to the ditch that extends along the southern boundary of the Arsynco property. The ditch located along the west side of the train tracks is a discharge point for groundwater west of the site. In addition, all of the ditches are discharge points for numerous point sources from industrial facilities in the region and all regional surface runoff (including Route 17 to the west). All of the ditches also receive daily tidal influx of poor quality surface waters from the Berry's Creek system, and this influx of tidal waters has occurred for at least a century. Historic, man made drainage ditches, which have previously been filled, are also likely to be primary flow paths through which shallow groundwater flows at the Arsynco site and the adjacent properties.

1.2 Stratigraphy and Hydrostratigraphy

1.2.1 Bedrock Aquifers

Carswell (1976) examined water supply in the Hackensack River Basin. The Hackensack River Basin is bounded to the west by the upland area that divides the Hackensack River Basin from the Passaic River Basin, and to the east by the Palisades Diabase Formation. The Arsynco site lies on the western portion of the Hackensack River Basin, in the lowlands valley very close to the topographic change in slope that begins the uplands area (see Figure B-5a of Geologic CSM).

Bedrock aquifers are the primary source of ground water in the Hackensack River Basin (Carswell 1976). The Brunswick Formation is the most hydraulically productive geologic unit. Production, however, is not uniform in the formation. Water is produced from heavily jointed zones (Carswell – 1976). These zones tend to parallel bedding, and the joints run primarily north-south along strike. The result is tabular units that are hydraulically separated vertically and that have strong anisotropy with preferred flow in the north-south directions (Carswell 1976).

1.2.2 Quaternary Aquifers

The surface geologic map and cross-sections of Stanford (1993) provide a basis for understanding the Quaternary aquifers in the Meadowlands region. In general, the salt-marsh deposits (Q_{m}) and the Lake Bayonne and Lake Hackensack lake-bottom deposits (Q_{bnl} and Q_{hkl}) will act as aquitards. The primary, regional Quaternary aquifers are the sand and gravel deposits of the Lake Bayonne lacustrine-fan (Q_{bnf}) and deltaic (Q_{bn}) deposits and the Moonachie Terrace deposits (Q_{mt}). Locally, the sandy portions of the Lake Hackensack lake-bottom deposits (Q_{hkl}) and the sandy areas of the post-glacial, tidally influenced areas (Q_{al}) will also act as aquifer material. In some locations these different lithologic units are in contact and will act as a single aquifer unit. Examples of this situation are apparent in wells MW-8D and MW-15D (see Figures B-6 and B-8 of Geologic CSM), where Quaternary alluvial units are in contact with the glacial Lake Bayonne deltaic deposits. Both units are interpreted to make up the deep (D-well) ground water zone at those locations.

Berry's Creek and the Hackensack River are the primary groundwater discharge points in the region. The Moonachie Terrace (Q_{mt}) and the Lake Bayonne deltaic (Q_{bn}) lithostratigraphic units to the west and northwest of the Arsynco site (see Figure B-2 of Geologic CSM) are both expected to act as aquifers. In terms of hydrostratigraphy, these lithostratigraphic units will act as a single, continuous hydrostratigraphic unit.

1.2.3 Site-Specific Distribution of the Quaternary Aquifers and Aquitards

The site geologic cross-sections (Figures B-6 through B-10 of Geologic CSM) provide a basis for interpreting the hydrostratigraphy at the Arsynco site. The location of these cross-sections is illustrated in Figure B-11 of Geologic CSM. The hydrostratigraphic interpretation is illustrated in those cross-sections, together with the current lithologic interpretation of the well logs.

On a local level, the artificial fill material (a_f and ${}^{s}a_f$) used to fill the salt-marsh (both on the site and in the region) is expected to act as conductive material. It is expected to be more conductive in the locations where it is composed of coarser material such as sand, gravel, and coarse construction material. These artificial fill deposits have been designated with a superscript s (${}^{s}a_f$). There appear to be areas where the fill material is also in direct contact with sandy areas of the salt-marsh deposits (Q_{al}). The Q_{al} deposits are interpreted to be the locations of former streams that drained the uplands during the time after the glacial lake had drained and the region was exposed to subaerial erosion (Stanford and Harper 1991; see Geology discussion in Section 4.4, above).

A good example of an alluvial channel eroded into the Lake Hackensack bottom-deposits (Q_{hkl}) is visible in wells MW-15D, MW-8D, MW-11D, and MW-11DD in Figure B-6 of Geologic CSM. The alluvial channel eroded the lake-bottom deposits, leaving alluvial sands. It is safe to assume that this alluvial channel drained off the uplands toward the center of the valley. The alluvial channel deposit is in direct contact with the glacial Lake Bayonne deltaic sands and gravels (Q_{bn}), which are the dominant lithology comprising the deep (D-well) groundwater zone. Therefore, the alluvial sands are part of the deep groundwater zone.

The S-well and D-well zones become a single, unconfined aquifer where the deltaic deposits (Q_{bn}) are exposed at (or close to) the surface. This occurs to the west and southwest of the Arsynco property. However, all wells that have been drilled on the Arsynco site encountered the Meadow mat and/or the confining clays and silty clays of the salt marsh deposits.

The silt and silty clays or clay (Q_m) of the salt-marsh deposits are expected to act as an aquitard between water in the shallow-well zone (S-wells) and the deeper-well zone (D-wells). A "dense" clay was encountered in several wells. This is interpreted to be the desiccated surface of the glacial Lake Hackensack lake-bottom deposits that occurred following drainage of Lake Hackensack to the north through the Sparkill Gap (see Section 4.4, above. In many areas of the site, the salt marsh deposits were laid directly upon the glacial Lake Hackensack lake-bottom deposits (Q_{hkl}), and both lithologic units will act together as a confining zone. These near-surface clayey deposits have been designated herein as the S-D (i.e., shallow - deep) confining zone in the present hydrostratigraphic interpretation.

The deep ground water zone at the Arsynco site (referred to as the D-well zone), is interpreted to be combinations of deltaic sands deposited during the Lake Bayonne stage (Q_{bn}) and the sandier portions of the Lake Bayonne bottom deposits. The silty, sandy clays described in some of the well logs have been interpreted as the distal portions of the prograding delta, and are designated on the cross-section figures with a prefix superscript d ($^dQ_{bn}$). At these locations, the delta deposits (Q_{bn}) grade into the glacial lake bottom deposits (Q_{bnl}) via the distal deltaic deposits ($^dQ_{bn}$). An example of this interpretation can be seen in section BB' (Figure B-7 of Geologic CSM) extending eastward from well MW-13D.

The base of the D-well zone, where it has been identified, is interpreted to be the Lake Bayonne bottom-deposits (Q_{bnl}). These lake-bottom, varved clays were laid down prior to deposition of the deltaic deposits prograding into glacial Lake Bayonne (Q_{bn}).

The two deepest wells on the Arsynco site, triple cased wells MW-5DD and MW-11DD, are interpreted to be screened in very different lithologies and, thus, are interpreted to be screened in separate hydrostratigraphic units. Well MW-5DD appears to have penetrated what Stanford (1993) interpreted to be glacial Lake Bayonne lacustrine fan deposits (Q_{bnf}). Well MW-11DD appears to be screened within the glacial Lake Bayonne lake-bottom deposits (Q_{bnl}). Therefore MW-11DD has been interpreted to be screened in the D-DD confining zone separating the D-well ground water zone from the DD-well ground water zone. The screens of both wells are set at overlapping elevations. The similar water levels in both wells is either a coincidence or the wells may be linked hydraulically in a fashion similar to the way the Lake Bayonne delta deposits grade into the lake-bottom deposits. There is currently insufficient information to distinguish between these two possibilities.

The hydrostratigraphy of the northwest corner of the Arsynco site is illustrated in Figure B-10 of Geologic CSM. The hydrostratigraphic cross-section extends east northeast onto the adjacent Northern Eagle property, passing very close to well MW-17 on the Cognis/Henkel site. The Cognis/Henkel site is connected hydraulically to the Arsynco site through the shallow (S-well) ground water zone and through the deep (D-well) ground water zone via the distal glacial Lake Bayonne deltaic deposits which are present in the subsurface at the locations of off-site wells MW-29D and MW-30D which are located on the Northern Eagle Beverage property along its border with the Cognis/Henkel site.

1.3 Regional Ground Water Flow

The surface geology in the vicinity of the Arsynco site is characterized by its glacial nature, with the exception of the salt-marsh deposits, the alluvial sands, and artificial fill. Table C-1 provides median hydraulic properties for glacial environments in the Northeastern Appalachian Hydrogeologic Region (Randall et al. 1988).

1.3.1 Bedrock Ground Water Flow

Figure C-4 illustrates the expected, dominant pattern of regional ground water flow in west-east cross-section in the vicinity of the Arsynco site. This conceptual model was generated assuming minimal or no anthropogenic influences. The geologic cross-section was digitized from Stanford's map (1993) and is the same cross-section as Figure B-3 of Geologic CSM. The distinction of the bedrock units was taken from Avery et al. (1996). The conceptualization of ground water flow is based on Randall et al. (1988, p.178) and from Carswell (1976).

The primary source of ground water in the Hackensack River Basin is the Passaic Formation (previously known as the Brunswick Formation, Carswell 1976). Flow is through joints, fractures, and parting surfaces or solution openings (Carswell 1976). Some beds have more openings than others. The resulting bedrock ground water system consists of a series of alternating aquifers and aquicludes several tens of feet thick and dipping toward the northwest at approximately 10 degrees (Carswell 1976).

The upland areas generally serve as recharge zones for ground water in the bedrock aquifers (Randall et al. 1988; Carswell 1976). Carswell (1976) measured flow in six uncased upland wells in Woodcliff and Park Ridge Boroughs in Bergen County under non-pumping conditions using injections of brine slugs. All six wells showed relatively strong downward flow in their boreholes indicating decreasing hydraulic head with increasing depth. Hence, the upland areas are areas of recharge for the bedrock aquifer.

The lowland areas are generally discharge zones for the bedrock aquifers. Carswell (1976) also measured flow in uncased boreholes in seven lowland wells in bedrock of the Hackensack River and Pascack Brook valleys. Four of the wells showed no detectable flow over the course of 30 minutes. However, the other three wells yielded upward flow, with two of the wells even discharging freely to the land surface. These results indicate increasing hydraulic head with increasing depth. Hence, upward flow occurs in the bedrock valley.

The primary, regional flow pattern is from the uplands into the Hackensack River valley, although there is also a strong bias that imparts a distinct, overall, three-dimensional pattern. The Passaic Formation is anisotropic with respect to ground water flow, with north-south trending fracture and joint zones introducing a strong bias for flow in those directions (Carswell 1976). Herpers and Barksdale (1951) reported results of a pump test in which drawdown was observed in a well 2400 feet from the pumping well along the strike of the formation. A different observation well that was only 600 feet from the pumping well, but in a direction perpendicular to the strike, showed no drawdown. Similar observations of the anisotropy in the Passaic Formation have been reported by other workers (Vecchioli 1967; Vecchioli et al. 1969). Therefore, when examining the flow pattern illustrated in Figure C-4, it is important to remember the third dimension into and out of the plane of the paper figure, since the cross-section is nearly perpendicular to the formation strike. Much of the flow may have to wind back and forth along that third dimension before it can move southeastward.

1.3.2 Ground Water Flow in the Quaternary Aquifers

Lacustrine-fan deposits are present at the lowest levels of the quaternary deposits in the region of the Arsynco site as illustrated in the Stanford's (1993) north-south cross-section included here as Figure B-4 of Geologic CSM. It is also interpreted to form part of the DD-ground water zone from the log for well MW-5DD, as illustrated in Figure B-7 . This deposit is shown to be in direct contact with the bedrock aquifer in the vicinity of the Arsynco site (near wells 109 and 210 in the cross-section of Figure B-4 of Geologic CSM). The locations of wells 109 and 210 are also included on Figure B-2 of Geologic CSM. The analysis of regional ground water flow in the bedrock aquifer discussed above (see Figure C-4) suggests that upward flow of ground water through this unit may be expected as ground water discharges into it from the bedrock.

The Lake Bayonne deltaic deposit (Q_{bn}) is continuous in the subsurface for some distance north of the Arsynco site, as illustrated in Figure B-2 of Geologic CSM. As discussed above, the Lake Bayonne deltaic deposit (Q_{bn}) is expected to by hydraulically continuous with the Moonachie Terrace deposit (Q_{mt}). Run-off from the glacial till-covered uplands west and north of the Arsynco site is expected to recharge both of these deposits. Therefore, groundwater flow is expected to be predominantly toward the southeast, approximately perpendicular to the uplands boundary. The discharge point of shallow groundwater is expected to be into the tidal ditches and ponds connected to Berry's Creek, with the deeper ground water (equivalent to the D-well zone at the Arsynco site) passing into the coarser portions of the varved Lake Bayonne and Lake Hackensack bottom deposits (Q_{bnl} and Q_{hkl}).

Regional ground water flow in map view is illustrated in Figure C-5. The ground water divide is based on the topography of the highlands areas of Rutherford, East Rutherford, Carlstadt, and Wood-Ridge. Infiltration and ground water flow in the Rahway Till (Q_t), as well as runoff, will supplement infiltration into the Lake Bayonne deltaic deposit (Q_{bn}) that lies between the till covering of the uplands and the artificial fill (a_f) and salt-marsh deposits (Q_m) of the Meadowlands. Ground water flow tends to get focused through higher transmissivity zones in regional flow patterns (Fetter 1994). Therefore, ground water flow coming off the uplands will be focused into the deltaic deposit sediments. The result is that a strong component of south to south-southeast regional ground water flow would certainly be expected along the northern boundary of the Arsynco site. The dominant flow pattern expected in the main portion of the site is toward the southeast. These patterns are clearly illustrated in Figure C-5.

The regional ground water analysis illustrated in Figure C-4, suggesting upward flow and discharge to the surface, is supported by historical topographic maps (Smock and Vermeule 1896; Wilson 1901), where the areas of Rutherford and Carlstadt and the adjacent marshlands are labeled as "Boiling Springs" (see Figures C-1 and C-3). Tolman (1937, p. 441) noted that "The term boiling spring is ... applied to springs issuing with sufficient force to agitate violently the water and bottom sand ....". These results, as well as the water levels consistently observed in the confined wells on the Arsynco site, clearly indicate that there are strong upward hydraulic gradients in the region of the Arsynco site.

Anthropogenic influence due to heavy pumping of the bedrock aquifer is likely to have reduced, to some degree, the magnitude of the upward hydraulic gradients over the past 50 years. However, it is expected that overall, regional pumping from the bedrock aquifer has likely decreased in recent years.

Details of the local ground water flow patterns will depend on the local geometry of the different geological deposits, the locations of tidal creeks/drainage ditches and their connections with the local ground water, and any anthropogenic influences imposed on the regional and local flow patterns. The local flow will be transiently influenced by the tide to varying degrees depending on the hydraulic connection between the local ground water zones and the tidal creeks and drainage ditches. This topic is discussed in detail below.

1.4 Site Ground Water Flow

The surface geology in the region of the Arsynco site consists of glacial and glaciofluvial deposits, salt marsh deposits, and artificial fill. Figure B-2 of Geologic CSM is a map of the surface geology in the site region. The site is almost entirely underlain by artificial fill material and estuarine and salt marsh deposits, as noted in previous Arsynco report submittals. The only exception may be along the western section of Tract 1, where deltaic sands and gravels were deposited into glacial Lake Bayonne. The presence of these surface deposits (although fill material may be present above these deposits) explains the thinning of the Meadow Mat encountered in the boreholes for wells MW-7S and MW-18D.

General patterns of ground water flow based on recent ground water contour maps are discussed in the following sections. Hydraulic conductivity results from site wells are presented in Table C-2. Subsequent sections address in detail the causes of water level variations at the Arsynco site. The three (3) most recent rounds of water level contour maps are also discussed in detail to demonstrate how the causes of variation affected the results in each of the six maps (three shallow and three deep flow maps).

1.4.1 Shallow (S-well) Water Zone

Figures C-6, C-7 and C-8 are water level contour maps for the shallow (S-well) ground water zone. Figure C-6 is from March 4, 2002. Figure C-7 is from May 31, 2002, and Figure C-8 is from May 19, 2003. It should be noted that greater detail was available for preparing the water table map for May 19, 2003 because of the addition of several new wells. Variation in the pattern of ground water flow between the maps is predominantly due to the measurement of water levels at different times during a tidal cycle. However, the timing in relation to precipitation and consequent recharge is also an important factor at this site. The tidal influence is discussed in greater detail in Section 4.5.5. These causes of water level variation are discussed in greater detail below.

The highest ground water level recorded in the shallow zone for all three (3) dates was at well MW-15S. This has been consistent throughout the history of that well. The vertical gradient was upward in seven of the eight rounds of water levels for which maps have been prepared that included the MW-15 cluster (July 1996, January 1997, April 1998, July 1999, March 2001, May 2002, and May 2003). The exception was the March 2002 date.

Similarly, the highest ground water levels in the deep (D-well) zone are recorded at well MW-15D. The combination of the high ground water levels in both wells MW-15S and MW-15D, along with the general upward vertical gradient, suggest that the area of well MW-15D was historically a spring. Again, this is consistent with the historical topographic maps describing the marshland areas as characterized by "boiling springs", as discussed previously. Examination of the April 16, 1959 aerial photo of the site also indicates that a stream channel existed in the area of MW-15, north of Building 1, and that tidal drainage ditches on the Cognis/Henkel property were tied directly into this stream channel. This provides additional support for the conclusion that the area around the MW-15S/D cluster was the site of a spring. The hydrostratigraphic cross-section of Figure B-10 of Geologic CSM also supports the interpretation that a former spring was located near the area of MW-15D. The highly permeable glacial Lake Bayonne delta complex sands thin dramatically between MW-28D and MW-15D and are essentially absent at well MW-29D. The result is consistent with what Tolman (1937, pp. 452-453), in his classification of springs, called a Class III spring, "Springs Issuing from Interstratified Pervious and Impervious Formations."

Ground water flow in the shallow zone is predominantly toward the south and/or east, depending on location at the site. Flow toward the southwest occurs in the extreme northwest corner of the site (see Figures C-6 to C-8). This pattern is the result of the presence of the historic spring near the MW-15S/D cluster and the tidal cycles. In the southwest portion of the site, the flow is predominantly to the south, although the precise flow direction in this area varies between south-southwest and south-southeast depending on the tides and location along the southern portion of the site.

Focusing of shallow groundwater flow into the locations of former tidal ditches (i.e., buried ditches or channels) can be seen along the northern portions of the Arsynco site in Figures C-6 and C-8. The pattern of drainage along the northeast portion of the site has been consistent since 1995. The pattern of drainage in the vicinity of the new off-site wells (MW-29S and MW-30S) is based on the presence of a former tidal drainage ditch that ran along the northern boundary of the Arsynco property in the approximate location of the Northern Eagle access driveway and the adjacent Henkel property. This former drainage ditch was identified in historic aerial photos of the site and was present through the 1966 photo, but was filled in between 1966 and the photo taken on 8/11/1968. The focusing of flow through the former, buried tidal drainage ditches in the March 4, 2002 map (Figure C-6) is due to measurement of water levels at a low tide stage. The focusing of shallow flow in the May 19, 2003 map (Figure C-8) is due to a combination of higher precipitation during the winter of 2002-2003 than had been experienced for several years, combined with the timing of measurement with respect to the tidal cycle.

Shallow groundwater flow is consistently toward the east in the northeast portion of the site. For all three dates (March 2002, May 2002 and May 2003), ground water flow comes onto the Arsynco site from the north (i.e., from the Cognis/Henkel site onto the Arsynco site).

1.4.2 Deep (D-well) Water Zone

Figures C-9, C-10, and C-11 are piezometric surface contour maps for the deep (D-well) ground water zone. Figure C-9 is from March 4, 2002, Figure C-10 is from May 31, 2002, and Figure C-11 is from May 19, 2003.

The March 4, 2002 direction of groundwater flow in the deep zone (Figure C-9) is onto the Arsynco site from the north in the northwest corner of the site. In the southeast corner of the site flow is directed to the southeast, off-site. These patterns are consistent with the regional ground water flow illustrated in Figure C-5. Southwest to west-southwest flow is indicated in the southwest area of the site. This appears to be a local pattern of flow imposed on the regional pattern by a possible connection between the tidal drainage ditches to the west and southwest of the Arsynco site (on opposite side of train tracks) and the tidal influence on ground water flow. This is discussed in greater detail below.

A ground water divide is indicated on the March 4, 2002 piezometric surface contour map (Figure C-9). The divide is in the shape of a "J" lying on its side running from approximately MW-15D through MW-5D and MW-10D. Ground water flow is toward the east on the northern side of the divide. Ground water flow is toward the southwest on the southwest side of the divide, and flow is to the southeast on the southeast side of the divide. A stagnation point lies in the vicinity of the former location of Building 2. The stagnation point marks the change in ground water flow direction on the south side of the divide.

In contrast to the March 4, 2002 piezometric surface contour map (Figure C-9), the May 31, 2002 piezometric surface map (Figure C-10) indicates a strong component of ground water flow coming onto the Arsynco site from the southwest toward MW-6D, where flow is then directed more to the east-southeast, toward MW-12D. There is still a ground water divide that appears to pass through or near wells MW-5D and MW-10D, but the divide is much less curved, running to the west near wells MW-16D and MW-18D. To the north of the divide (in the area of wells MW-15D and MW-8D), ground water flow is onto the site from the west and north and is directed toward the east. Flow is onto the site from the southwest, with off-site flow toward the southeast on the southern side of the divide. The stagnation point marking the changes in flow has shifted toward the east, lying near former Building 18.

Greater detail was available for preparing the piezometric surface map for May 19, 2003 (Figure C-11) because of the addition of several new, off-site wells (MW-27D, MW-28D, MW-29D, MW-30D, and MW-32D). A ground water divide is still evident in the May 19, 2003 map. The ground water divide on this date ran east-west from MW-27D through MW-16D, MW-5D, and MW-10D. Ground water to the north of the divide (and along the northern site boundary) flows to the east, toward the area around well MW-9D. On the eastern portion of the site, flow is directed into the varved fine sands, silts, and clays of the glacial lake bed deposits. Two (2) primary flow paths are apparent. On the north side of the ground water divide, ground water is focused toward and follows a path running from MW-18D toward MW-8D to just north of MW-22D and MW-11D, and then flows east toward MW-9D. South of the ground water divide, flow is toward the east-southeast from MW-17D toward MW-13D.

The consistent presence of a ground water divide trending toward the east-southeast between wells MW-5D and MW-10D is supported by the hydraulic conductivity measurements made previously at the site and that were discussed in the 1997 RIR submittal. Well MW-10D had lower hydraulic conductivity (0.0120 ft/day) than wells MW-9D (0.0730 ft/day) and MW-13D (0.0477 ft/day) that are to the north and south, respectively.

1.4.3 Causes of Water Level Variation at the Arsynco Site

The physiographic setting of the Arsynco site leads to two (2) major sources of water level variation. The first is the tide cycles via the Hackensack River, Berry's Creek and the tidal drainage ditches. The second is the combination of precipitation and the proximity to the highlands west of the site. These sources of variation are discussed in detail below.

Precipitation and Timing of Recharge

The Arsynco site is located in close proximity to the highlands along the western boundary of the Hackensack River valley (see Figure B-5 of Geologic CSM). These highlands are covered by glacial till (see Figure B-2 of Geologic CSM). Till deposits generally have relatively low permeability (see Table C-1). A significant fraction of precipitation falling on the highlands is therefore expected to runoff down the hill slope. This will be compounded by the urban nature of the region. More of the precipitation and runoff is expected to infiltrate beginning where coarser Lake Bayonne deltaic deposits abut the highlands. This occurs where the break in slope (illustrated in Figure B-5 of Geologic CSM) is located. This infiltration is expected to recharge the deep ground water zone in the area of the Arsynco site. However, the recharge will take time to reach the deep groundwater zone due to the time it takes for the infiltration and ground water flow to occur. Infiltration into the shallow zone, on the other hand, is expected to be very rapid, occurring within a short time of moderate to large precipitation or snow melt events. Therefore, the relative timing of recharge in the shallow and deep zones must be considered when interpreting their respective water level responses.

A precipitation database, containing historical monthly precipitation data for stations in New Jersey, was acquired from the National Climate Data Center (NCDC 2003). Data from the following stations were used to generate regional, average values for suburban northeast New Jersey: Chatham, Cranford, Elizabeth, Essex Fells, Irvington, Jersey City, Little Falls, Lodi, Midland Park, Newark International Airport, New Milford, Orange, Paterson, Rutherford, and Woodcliff Lake. Years for which the monthly records were incomplete at any station were discarded from all cumulative, total calculations.

It is important to evaluate the precipitation records in the weeks (and, sometimes, months) leading up to dates when water level measurements were taken at the Arsynco site because of the expected recharge effects. The location of the Arsynco site near the western edge of the Meadowland lowlands (and along the eastern edge of the glacial till covered highlands) means that groundwater at the site will respond relatively quickly to precipitation and recharge events. This was evident during both the tidal study conducted at the site in 1995 and the recent tidal study conducted at the site in 2003, as discussed in greater detail below. The nearest location where precipitation records are kept is Teterboro Airport, which is located approximately 1½ to 2 miles north of the site. Data from Teterboro Airport were also obtained from the National Climate Data Center.

Precipitation records at Teterboro Airport are often spotty, with numerous daily records missing in the historical record. Newark International Airport has nearly complete records. Correlation was examined between the Newark records and the Teterboro records for 217 matched, daily precipitation records from January through August 2003. Three (3) correlations are presented in Figure C-12. The first contains all 217 records, where the correlation coefficient (r) was 0.7363. The second was made discarding records where either site had more than 1.5 inches of precipitation in a day, leaving 209 records, where the correlation coefficient (r) was 0.7852. The third correlation was made discarding records where either site had more than 1.0 inch of precipitation in a day, leaving 204 records, where the correlation coefficient (r) was 0.8114. While the correlations are not perfect, they do indicate a high degree of correlation, as would be expected.

Table C-3 contains the precipitation records for Teterboro Airport and Newark International Airport for the period of two (2) weeks prior to the dates when water levels were measured for the three (3) most recent rounds of water level measurements at the site. The potential importance of missing precipitation records from Teterboro is apparent for the March and May 2002 ground water maps. A large precipitation event occurred at Newark International the day before water levels were collected for the March 4, 2002 maps. A large precipitation event was also recorded at Newark International approximately two (2) weeks before water levels were collected for the May 31, 2002 maps. Both of these precipitation events went unrecorded at Teterboro Airport. Although the May 2002 precipitation event is likely unimportant for the shallow zone since it occurred so far before the water levels were obtained, it will be more important for the deep zone. The March 2002 precipitation event, occurring the day before measurements were obtained, is of significant importance for the shallow zone, but will not likely have reached the deep zone in that short of a time span.

Relatively little precipitation occurred during the two (2) weeks prior to obtaining the water levels for the May 19, 2003 ground water maps, and the majority of that precipitation occurred approximately a week and a half prior to the measurements.

Tidal Influence on Ground Water Flow

Groundwater in the area of the Arsynco site is tidally influenced via the Hackensack River, Berry's Creek, the tidal ditches surrounding the site on three (3) sides and the large pond on the Henkel property to the north. The tide-curve pattern for the Hackensack River, running from one full moon to the next, is illustrated in Figure C-13. The pattern is semi-diurnal, with two (2) low and two (2) high tides occurring most days. This is typical for the east coast of the United States (International Marine 2003). The lunar or tidal day is about 50 minutes longer than the solar day, causing the tide to occur at successively later times each day (International Marine 2003). When a high or low occurs close enough to the end of the day, the subsequent, corresponding tide will skip a day. This results in an occasional day when only one high or one low tide occurs (International Marine 2003).

The magnitude of the tidal range (difference between successive high and low tides) varies with the Moon's distance and phase. These changes are illustrated in Figure C-14, which is based on the data used in Figure C-13. The tidal range is greatest at full moon (approximately 7.3 to 8.8 feet). A secondary maximum in the tidal range occurs at the new moon phase (approximately 6.9 to 7.4 feet). The minimum tidal range occurs at the last quarter phase of the moon (approximately 3.6 to 4.4 feet). Finally, a secondary minimum occurs at the first quarter phase (approximately 5.0 to 6.5 feet). Therefore, the magnitude of the tidal driving forces influencing ground water flow varies with the lunar cycles.

The relative magnitude of the tidal driving forces acting on the ground water at the Arsynco site are assumed to follow a similar pattern as that illustrated in Figures C-13 and C-14 for the Hackensack River. The USGS maintains a real-time gauging station at the Hackensack River (Hackensack, NJ station). The gauge height is recorded at six (6) minute intervals at this location. The most recent week's worth of data can be downloaded from the following URL: http://waterdata.usgs.gov/nj/nwis/uv/.

A semi-quantitative assessment was made of the magnitude of tidal fluctuations in the tidal ditches bordering the Arsynco site during site visits on December 3 and 4, 2002. Visual examinations of the southern drainage ditch bank were made on December 3, 2002. The water level at 2:38 PM was estimated to be approximately 2 to 3 feet below what appeared to be the high tide level based on ice remaining attached to the bank.

The tide in the ditches was noted to be at or near slack high upon arrival at the site at 9:55 AM on December 4, 2002, as there was no perceptible flow of water at the culvert passing under 13th Street on the south end of the site or at the culverts passing under 16th Street on the eastern boundary of Tract 2. Higher high tide was predicted to be 7.8 feet above MSL at 9:02 AM (on December 4, 2002) at the Hackensack River substation at Hackensack, NJ (International Marine 2002). This time was approximately ½ day before the new moon (International Marine 2002). At 2:04 PM (on December 4, 2002), the water level at the 16th Street culvert at the northeast corner of Tract 2 of the site was measured to have fallen approximately 4-feet 4-inches, with an estimated error of ±2 inches based on the wetted line remaining on the concrete culvert. The wetted line was assumed to mark the high tide level. The predicted, lower low tide at the Hackensack substation was -1.2 feet MSL at 3:40 PM (on December 4, 2002). These results suggest that the tidal range at the Arsynco site is on the order of one-half that predicted for the Hackensack River at the Hackensack, NJ substation. Although these results are not sufficiently controlled to make quantitative predictions for the site, they can be used to provide semi-quantitative estimates of the tidal response at the Arsynco site.

Two (2) tidal studies have been conducted at the Arsynco site. The first study was conducted February 16-22, 1995 and was discussed within the 1997 RIR submittal for the facility. A more recent and focused study, examining tidal influences on flow along the northern boundary of the Arsynco site, was conducted during the period June 13-16, 2003. Tidal influences were documented in both studies, but both studies were also significantly complicated by recharge events that occurred before and during the study periods. Online data for the Hackensack River were not available for the February 1995 study, but data was obtained for the period of the June 2003 study.

Ground water flow in both the shallow (S-well) and deep (D-well) zones is tidally influenced as indicated during the tidal study conducted in 1995 and documented in the 1997 RIR submittal for the site. Water levels were recorded every 15 minutes in wells MW-8S, MW-8D, MW-10S, MW-10D, MW-12S, and MW-12D for approximately six days from February 16, 1995 to February 22, 1995. A major snow-melt occurred during the course of the 1995 tidal study, and the resulting recharge dominated the water levels in the shallow wells, largely obscuring the daily tidal cycle pattern.

The tidal influence explains a large part of the variation in ground water flow that is recorded in the shallow-water zone (S-well) maps and the piezometric surface maps for the deep-water zone (D-well) between 1995 and 2003 at the Arsynco site. Each such map portrays an approximate "snap-shot" of the ground water behavior at one point during a tidal cycle. This is illustrated graphically in Figures C-15 through C-24. The vertical lines on Figures C-15 through C-24 bound the time interval during which water levels were collected for preparation of ground water flow maps at the Arsynco site. Table C-4 provides data regarding the phase of the moon and approximate time in the tidal cycle for the dates water levels were collected for preparing ground water maps. Examination of Table C-4 and Figures C-15 through C-24 demonstrates that each round of water levels were collected at a different time within the lunar cycle and tidal cycles. Variations in precipitation occurring in the days and weeks prior to collecting the water levels will also introduce variations in the ground water maps, as discussed above.

The recently installed monitoring wells (MW-17S/D through MW-32S/D clusters) provide additional data points that can be used to more accurately determine the specific patterns of tidally influenced changes in ground water flow.

Detailed analysis of the two (2) tidal studies conducted at the site is presented in the following subsections.

1.5 Site Tidal Study –February 16-22, 1995

The results from the previous tidal study conducted at the site from February 16 to 22, 1995 are plotted in Figures C-25 through C-33 in terms of elapsed time from a reference date and time of 12:00 AM February 16, 1995. The 1995 study was started the morning after a full moon and ran until approximately a half day before the last quarter moon. Therefore, the expected pattern of tidal cycle influence on site groundwater would go from its maximal effects to its minimal effects (see Figure C-14).

1.5.1 Tidal Influences in the Shallow (S-Well) Water Zone

Figures C-25, C-26, and C-27 are plots of water levels in shallow-water wells (S-well zone) during the 1995 tidal study. The influence of the snow-melt event is clearly visible in the MW-10S and MW-12S water levels (Figures C-26 and C-27, respectively). The mean water level in those wells rose during most of the six (6) day study, beginning to decline only in the last one-half day.

The recharge and tidal cycles are strongly confounded in the water level pattern that occurred in MW-8S (see Figure C-25) during the 1995 study. Tidal cycles are clearly apparent in this well, but they do not follow the expected diurnal pattern. The magnitude of water level swings due to the tides decreased over the course of the study, as would be expected given the timing of the study with respect to the lunar cycle.

Recharge occurred from the beginning of the test in MW-10S (Figure C-26) and continued through to approximately day 5.0 to 5.4 of the study. The water levels began to fall after that time. Tidal cycles are apparent on a semi-diurnal basis in the early part of the study, but are not apparent in the last day and a half. Again, this is consistent with the magnitude of tidal influences diminishing with elapsed time during the test, as the lunar cycle approached the last quarter moon. The overall pattern reflects the interaction between the recharge event and the tidal cycles.

Recharge in well MW-12S is apparent from the start (Figure C-27) of the 1995 study. The water level in MW-12S rose rapidly to approximately day 2.4, then rose slowly thereafter until approximately day 5.0. The water level in well MW-12S then began to decline beginning at approximately day 5.8. The recharge from the snow melt completely swamped the tidal cycle signal in this well, and there are only minor peaks which are likely related to the tide cycle.

The influence of the tide cycle can be clearly seen superimposed on the general trend of rising water levels due to the snow melt recharge event in well MW-10S (Figure C-26). The tidal influence in well MW-12S is mostly masked by the recharge event (Figure C-27). Two (2) minor peaks show up around elapsed times 2.1 and 3.25 days, which correlate roughly with two (2) of the broad peaks in well MW-10S.

1.5.2 Tidal Influences in the Deep (D-well) Water Zone

Figure C-28 is the water level time series for well MW-8D during the 1995 tidal study. Figure C-29 is the time series for MW-10D, and Figure C-30 is the time series for well MW-12D.

Recharge began in well MW-8D from the start of the 1995 study and continued through to approximately day 5.0 to 5.2 (Figure C-28). The early and continuous recharge in MW-8D reflects its proximity to the shallow deposits of the glacial lake delta to the west (Q_{bn} in Figures C-4 and C-5). The general water level began to decline after day 5.2. Minor tidal cycle influences are superimposed on the recharging water level but do not appear to become regularly apparent until about day 3.6. This pattern is due to the interaction between the recharge event and the tidal cycles, with the recharge event dominating the majority of the study.

The pattern of water levels in wells MW-10D and MW-12D during the 1995 tidal study were very similar. The general trend was for the water levels to increase slowly from approximately day 1 of the study through approximately day 3.2 to 3.4. The water levels began to rise much more steeply after that time, with the "running average" water level beginning to stabilize at approximately day 6.0 (essentially at the end of the test). The tidal cycles are clearly superimposed (Figures C-29 and C-30) on this overall pattern in both wells, but the amplitude of tidal cycle changes appears to increase toward the end of the 1995 test, nearly doubling beginning at approximately day 4.9. This increase corresponds with the leveling off of water levels in well MW-10S. This pattern is due to how the tidal influence is applied in the deep zone, particularly in the wells toward the eastern part of the site. The timing of the high water levels provides additional information to help understand how the tidal driving force is applied.

Table C-5 contains the timing of the tidal high-water levels in the three (3) D-series wells that were observed during the February 1995 tidal study. It is important to note that within a few hundredths of a day, the peak times in the different D-wells occur essentially simultaneously. The average time difference in high-water levels was only 0.018 days (26 minutes). There is also no regular pattern in the timing of these differences (e.g., peak levels in well MW-10D do not consistently occur prior to peak levels in MW-12D). Given the various distances of the wells from surface water bodies, these results support the conclusion that MW-10D and MW-12D are not directly connected with the tidal drainage ditches. This indicates that water in the D-well zone on the northern and eastern parts of the site is isolated from the surface.

Hydraulic head (h) in a piezometer or well is a combination of pressure head (P) and elevation head (z) (Freeze and Cherry 1979; Fetter 1994).

$$h = z + \frac{P}{\rho g} \qquad \text{(Equation 1)}$$

Pressure head (P) is normally thought of as being simply due to the weight of the overlying water column in a piezometer (Fetter 1994). This is the <u>measure</u> of the hydraulic head (h). In a confined aquifer, the source of hydraulic pressure head is the overburden pressure from the weight of overlying sediments, water and atmosphere on top of and including the confining unit, plus the water head applied laterally through the confined aquifer unit. As the overburden pressure increases, the pressure head, and hence the hydraulic head measured in a piezometer, increases. The confining unit acts as a semi-rigid solid which distributes the load over a broad area. This is what explains the influence of atmospheric loading on a confined aquifer and also the influence of freight trains on water levels in a confined aquifer (Ferris et al. 1962; Lohman 1972). Therefore, piezometers situated in a confined unit with an overlying, tidally-influenced, water table aquifer can be expected to respond in a nearly synchronized fashion to the tidal load which is applied indirectly by tidal loading of the water table aquifer via the tidal creeks and ditches. This mechanism of applying the tidal force may also explain the tidal amplitude increases observed in wells MW-10D and MW-12D. As the increasing water levels in the corresponding shallow wells began to stabilize, the magnitude of the tidal loading became more significant in a relative fashion in the deeper wells. This explains why the inverse of the expected pattern of tidal influence occurred in these wells during the 1995 tidal study.

Significant accumulation of runoff and recharge to the shallow zone following a major precipitation event (or snow melt) are expected to mute the relative magnitude of the tidal cycle influence in the deep zone. As the recharge and runoff drains away, the magnitude of the tidal cycles increases.

1.5.3 Tidal Influences on Flow Between the Shallow and Deep Zones

Vertical gradients during the February 1995 tidal study were calculated as the difference (shallow – deep) divided by the thickness of the meadow mat clay layer separating the shallow and deep zones at each well. A positive gradient therefore indicates downward flow from the shallow-zone into the deep-zone. The influence of the large recharge event (snow melt) that occurred during the tidal study masks the pattern that would be expected on a normal basis.

The vertical gradient was directed downward at the beginning of the study in the MW-8S/D cluster, but the gradient decreased continuously throughout the study reversing to upward by day 4 (Figure C-31). The gradient reversal occurred as the recharge event brought water into the D-zone near cluster MW-8S/D and as the recharge water drained away, lowering the head in well MW-8S. The early and continuous recharge in MW-8D reflects its proximity to the shallow deposits of the glacial lake delta to the west (Q_{bn} in Figures C-4 and C-5). Upward flow is consistent with the regional ground water flow pattern illustrated in Figure C-4 and the expectation that the Meadowlands region is a ground water discharge zone.

The vertical gradient at well cluster MW-10 was initially upward during the 1995 tidal study (Figure C-32). The upward gradient is consistent with the expected cross-sectional regional ground water flow pattern illustrated in Figure C-4. The initial upward gradient declined and reversed to a downward gradient by approximately day 0.7. Downward gradients persisted through the remainder of the study, but appeared to be in decline beginning at approximately day 5. Tidal cycles are clearly superimposed on the vertical gradient (Figure C-32), but appear to follow a diurnal pattern rather than the semi-diurnal pattern that was apparent in well MW-10D. This is likely to be the result of the interaction between the recharge event and the tidal cycle. The amplitude of the tidal cycle influence (the variation around the "running average" gradient) was approximately ±0.09 ft/ft.

The vertical gradients were downward throughout the 1995 tidal study at the MW-12 well cluster (Figure C-33). The magnitude of the vertical downward gradient increased sharply during the first two days of the study, but the average vertical gradient declined continuously through the remainder of the study. Tidal influences are clearly superimposed throughout the study (where). The amplitude of tidal cycle influence (the oscillation about the "running average" gradient) was approximately ±0.07 to ±0.08 ft/ft.

1.6 Site Tidal Study – June 13 to 16, 2003

1.6.1 Tidal Study Design

A 72-hour tidal study was completed from June 13 to 16, 2003 to determine the behavior of groundwater flow and the degree of tidal influences for both the shallow, perched water zone (S-well zone) and the groundwater below the meadowmat/clay layer (D-well zone) along the northern boundary of the Arsynco site. The 72-hour tidal study was conducted using In-Situ miniTroll data loggers equipped with 30 psi pressure transducers installed in 12 monitoring wells (6 shallow wells and 6 deep wells). The miniTroll units were installed in on-site, shallow wells MW-8S, MW-14S, MW-15S and MW-22S and in newly installed off-site, shallow wells MW-29S and MW-30S, located just north of the Arsynco property. The deep wells included in the study included on-site wells MW-8D, MW-14D, MW-15D and MW-22D and off-site deep wells MW-29D and MW-30D. The pressure transducers were installed on the morning of June 13, 2003, and both temperature and water levels were measured in each well at 30 second intervals for a period of 72 hours.

1.6.2 Background

Tide data for the Hackensack River at the Hackensack, NJ gauging station are presented graphically in Figure C-34 for the interval from June 11-18, 2003. Table C-6 contains a description of the tidal peaks and troughs recorded at the Hackensack station during the time interval bracketing the June 13-16, 2003 tidal study conducted at the Arsynco site. The times used for all graphs of tidal results are expressed as elapsed time, in days, from a reference time of 5:00 AM June 13, 2003.

The Hackensack River tidal gage station data have been overlain on all graphs showing tidal response for the June 2003 study in order to illustrate the correlation between the tidal driving force and the ground water response. To facilitate the comparison, the river gage data were scaled such that the scaled tidal range was comparable to the range of the specific data set of interest. The scaling was performed using the following equation:

$$H_R^s(t) = H_R(t) * \frac{s_{ref}}{s_{H_R}} + \overline{\Delta H} + \frac{\overline{\Delta H_{ht}}}{\varepsilon}$$

where $H_R^s(t)$ is the scaled river gage height at time t, $H_R(t)$ is the actual river gage height at time t, s_{ref} is the standard deviation of all ground water elevations examined in the graph, s_{H_R} is the standard deviation of the river gage height, $\overline{\Delta H}$ is the difference between the average of all water levels in the wells of interest and the average tidal gage height, $\overline{\Delta H_{ht}}$ is the average difference between successive high tide gage heights, and ε is an arbitrary scaling factor.

1.6.3 Precipitation Effects

Abnormally high precipitation occurred in late May and early June 2003 in the area of the Arsynco site. Data from Teterboro Airport for 2003 and averages from the region are presented in Table C-7.

The regional, average precipitation through May 2003 was 18.61 inches with a standard deviation of 4.84 inches. Cumulative precipitation at Teterboro airport through May 2003 was 17.44 inches. This is 0.24 standard deviations below the regional average. The regional, average, cumulative precipitation through June 2003 was 22.27 inches with a standard deviation of 5.44 inches. Precipitation at Teterboro Airport through June 2003 was 26.90 inches. This is 0.85 standard deviations above the regional average. Therefore, between the end of May and the end of June 2003 precipitation went from below average to above average.

The regional average precipitation in June 2003 was 3.69 inches, with a standard deviation of 1.99 inches. Prior to the start of the tidal study (June 13, 2003), more rain had already fallen (5.66") than the average for the whole month of June. By the end of the tidal study (June 16, 2003), 6.94 inches of rain had fallen at Teterboro Airport. These amounts are approximately 1.63 standard deviations above the normal for the whole month. The June 2003 cumulative precipitation at Teterboro Airport was 9.46 inches, which is 2.90 standard deviations higher than normal for the region. This pattern of rainfall enormously complicated the analysis of the June 2003 tidal study data for the Arsynco site.

Precipitation data for Teterboro Airport for May and June 2003 are presented graphically in Figure C-35. The start and end times for the tidal study are also illustrated for reference. Approximately 10 inches of rain fell on the area in the weeks prior to the start of the tidal study. The rain began May 21st, and over 5 inches of rain fell between June 1st and 8th, with at least some rain falling every day except June 6th. Large amounts of rain fell on June 1st (1.95"), 3rd (1.37"), 7th (0.76"), and 8th (0.76"). Three (3) days of no rain (9th through the 11th) passed, then another 0.34" fell on June 12th, the day before the study started. Additional rain fell during the study: 0.71" on June 13th, 0.57" on the 14th, and 0.34" on the 15th. The precipitation in early June caused longer-term trends in water levels in the site wells upon which the tidal influence, when detectable, was superimposed. Assuming that approximately 30% of the 10 inches of rainfall that occurred between May 20 and June 13 went to recharge the ground water, and assuming an effective porosity of 0.30, water levels in site wells would be expected to rise approximately 10 inches (i.e., approximately 0.8 feet).

1.6.4 Shallow Well Water Levels

The water level records for each of the six (6) shallow well monitored during the study are presented in Figures C-36 through C-41. In all six (6) wells the general, longer-term pattern is that of declining water levels as the high amount of precipitation that fell in late May and early June 2003 drained away. The water levels for all shallow wells are shown in Figure C-42. During the study, the relative magnitudes of water level changes were significantly different from well to well.

Tidal influences on hydraulic gradients in the shallow, S-well, zone were largely masked by the heavy precipitation preceding the study. Graphs of various hydraulic gradients in the shallow (S-well) zone during the tidal study are presented in Figures C-43 through C-51. The horizontal hydraulic gradients were calculated as the water level in the first well listed in the pair (see Figures C-43 to C-51), minus the water level listed in the second well (Figures C-43 to C-51), divided by the distance between the wells. This results in a "map gradient" which can be converted to the actual field gradient by dividing by the map scale conversion factor (39.37 feet/cm). The "map gradients" are more convenient numerically, and they still show the response pattern since they only differ by a constant multiplier from the actual gradients. Longer-term trends due to the high precipitation prior to the study are notable in most of the gradient graphs. Where the tidal influences are notable (see Figure C-45), their timing is obscured by the recharge events.

Figures C-52 through C-56 are water table contour maps for five (5) different times during the June 2003 tidal study. Examination of the water levels in the wells confirms the overall pattern of falling water levels in the shallow zone throughout the course of the study. Ground water flow on the western part of the monitored area (northwest part of site) is consistently from the north toward the south, from the Cognis/Henkel property toward the Arsynco property. Figure C-52 represents the water table at the approximate time of the first lower high tide, and Figure C-53 represents the water table at the approximate time of the second higher high tide. Ground water flow on the eastern part of the monitored area (northern site boundary) at these times is toward the south-southeast. Figure C-54 represents the water table at an intermediate time between the second higher high tide and the second lower low tide. Flow at this intermediate time on the eastern part of the monitored area was shifting as the tide went out, beginning to move in a more easterly direction. The hydraulic gradient also increases at this intermediate stage. These changes continue as water drains toward the east during the period of declining water levels in the tidal streams (i.e., outgoing tide). Figure C-55 represents the water table at the approximate time of the second, lower low tide, and the gradient from MW-30S to MW-14S is considerably steeper at this stage, with flow toward the southeast. Figure C-56 represents the water table at the approximate time of the third lower low tide. The pattern in Figure C-56 is very similar to that shown in Figure C-55 (i.e., steep hydraulic gradient between MW-30S and MW-14S, with flow toward the southeast).

At all times throughout the study ground water flow in the shallow zone was from the north, from the Cognis/Henkel property toward the Arsynco property, regardless of tidal stage.

1.6.5 Deep Well Water Levels

The water level records for each of the six (6) deep wells monitored during the June 2003 tidal study are presented in Figures C-57 through C-62. The influence of the recharge events beginning in late May 2003 and continuing through early June 2003 are clearly observed in the record for each well. The overall pattern in the deep wells is that of increasing water levels through approximately the first half of the study, followed by declining levels through the latter half of the study. This general, overall pattern is due to the recharge of the deep (D-well) zone from the Lake Bayonne deltaic deposits to the west, as discussed under the geology section (see Section 4.4). The pattern of higher water levels represents the smoothed out response of the recharge that occurred from May 21 through June 8 (see Figure C-35). Again, the longer-term pattern dominated the water level response compared with the tidal influence at most of the wells.

However, the response at well MW-14D was the exception (see Figure C-58). The water level response at the time of the higher high tides averaged approximately 0.157 feet in MW-14D, which was notably larger than all of the other deep wells. The tidal response at high tides in the D-well zone appears to occur slightly before the high tides at the Hackensack River gauging station at Hackensack, NJ. Using only the higher high tide peaks from well MW-14D, the tidal response at the Arsynco site occurred, on average, 0.03060 days prior to the high tides at the Hackensack River gauging station with a standard deviation of 0.00082 days. Therefore, the tidal highs at the Arsynco site occur approximately 44 minutes prior to the tidal highs at the USGS gauging station in the Hackensack River.

The water level response in well MW-15D experienced regular, short-duration spikes of approximately 0.01 to 0.015 feet (see Figure C-59). The source of these spikes is unknown, but their influence is negligible compared with the influence of the recharge event, and it is smaller than the tidal influence.

The water level response in MW-22D was relatively small and quite "noisy" (see Figure C-60). The noisy response is interpreted to be due to rapid rainfall infiltration focused into the large, stone-filled area of the former effluent treatment basin that was located south of Building 5 and adjacent to MW-22D. Infiltration into this stone filled area leads to a rapid loading of the shallow (S-well) zone and development of a mound at that location, applying a "point" load to the deep-well zone centered on the basin. This point load is observed in MW-22D because of its close proximity to the stone filled area. As water drains away from the basin through the S-well zone, the point-load is diminished at MW-22D as the load is spread over a larger portion of the S-D confining zone. This interpretation is supported by the water level response in well MW-22S (Figure C-39), which shows a broad rise and then fall imposed on the overall, declining water level. This is interpreted as the infiltration focused on the stone-filled basin south of Building 5 beginning to reach MW-22S, followed by passing of the infiltration event. The noisy response in MW-22D occurs because it is directly adjacent to the edge of the stone filled basin, while the broader, more gradual response in MW-22S is smoothed out because of the slightly greater distance of that well from the stone filled basin.

The early June 2003 recharge event almost completely swamped out the tidal response in MW-29D (see Figure C-61). The tidal response in MW-30D is more distinct, although the tidal response in 30D during the early portion of the study was masked by the arrival of the recharge pulse from the early June 2003 precipitation.

The relative magnitude of water level response between the different deep wells can be seen in Figure C-63, in which all the D-well water level curves are presented. On this scale, only the tidal response in well MW-14D appears significant, although the responses in MW-15D and MW-30D are observed.

1.6.6 Tidal Influence on Ground Water Flow in the D-Zone – Northern Boundary

Ground water flow in the deep, D-well, zone along the northern property boundary of the Arsynco site is influenced by tidal cycles. The patterns of tidal influences on the gradients between deep wells along the northern property boundary during the June 2003 tidal study are illustrated in Figures C-64 and C-65. While the tidal cycles did influence gradients between wells, the overall pattern of ground water flow along the northern property boundary was not significantly altered during the tidal cycles.

Ground water flow in the deep, D-well, zone during the June 2003 tidal study was dominated by the recharge occurring due to the rain in early June. Figures C-66 through C-70 are piezometric surface maps for the D-well zone along Arsynco's northern property boundary. Figures C-66 and C-70 bracket the beginning (first lower high tide in the Hackensack River) and end of the study (third lower low tide in the Hackensack River). Figures C-67 through C-69 are focused on the interval covering the second higher high tide through the second lower low tide at the Arsynco site. The variation in ground water levels was dominated by the longer-term pattern of recharge, as discussed above. While tidal variations in water levels did influence gradients between wells, the overall pattern of ground water flow remained essentially constant, as shown on the Figures.

The dominant pattern of flow in the deep groundwater zone (D-well zone) along Arsynco's northern property boundary is toward the east (onto the site from the west) and toward the southeast, onto the site from the north. The southeast flow regime recorded during the 72-hour tidal study indicates that deep groundwater (D-well zone) is from the Cognis/Henkel site onto the Arsynco property. This is consistent with historic data collected from the Arsynco site wells. Wrapping of the projected contours around Henkel's well MW-17, as shown on Figures C-66 through C-70, is based on four increasingly reliable lines of evidence. The first line of evidence is the stratigraphy, hydrostratigraphy, and the expected regional pattern of ground water flow as discussed above in Section 4.5.3. The second line of evidence is the historical piezometric surface maps for the Arsynco site, which have consistently indicated flow of ground water onto the Arsynco site from the north. The third line of evidence is the ability of ground water and contaminant transport modeling to explain the appearance of contaminants derived from the DNAPL in Henkel's well MW-17 in Arsynco well MW-8D; the groundwater and contaminant transport model report is provided in Appendix D of the 2003 RAW. The fourth line of evidence is the consistent pattern of ground water levels between wells MW-29D, MW-30D, MW-14D, MW-8D, and MW-22D. All of these lines of evidence support the conclusion that contaminated ground water is flowing from the Cognis/Henkel site onto the Arsynco property.

1.7 Analysis of Recent Ground Water Maps

Patterns in the ground water flow observed in the three (3) most recent ground water flow maps (March 4, 2002, May 31, 2002, and May 19, 2003) are explained in the following subsections in terms of the hydrologic understanding of the site. The dates of the maps (March 4, 2002, May 31, 2002, and May 19, 2003) were selected because sufficient hydraulic data were available from wells to generate a reasonable understanding of the tidal influences at the Arsynco site. Average site water levels were defined based on wells that were available for all three (3) dates in order to facilitate understanding some of the patterns. Average site water levels were calculated from shallow wells MW-4S through MW-26S and deep wells MW-5D through MW-25D.

Vertical head differences between ground water units were calculated as the shallow (S-well zone) water level minus the deep (D-well zone) water level ($\Delta h_{SD} = h_S - h_D$), and as the deep (D-well) water level minus the water level in the triple cased, "DD" wells (DD-well zone) ($\Delta h_{DD} = h_D - h_{DD}$). Therefore, negative values for the head difference calculations indicate upward ground water gradients and upward flow.

Vertical head differences for the different shallow/deep (S/D) well clusters are presented in Table C-8. Vertical head differences for the two (2) deep (D-zone) and DD-zone well clusters (MW-5D/MW-5DD and MW-11D/MW-11DD) are presented in Table C-9. Three (3) distinct head-difference averages for the shallow/deep head differences (Table C-8) were defined based on the time sequence of new well installation. This was done to keep each average value comparable over the different dates. The first average head difference shown on Table C-8 included the following clusters: MW-5S/5D, MW-8S/8D, MW-9S/9D, MW-10S/10D, MW-11S/11D, MW-12S/12D, MW-13S/13D, MW-14S/14D, and MW-15S/15D. The second average on Table C-8 included all clusters in the first average plus well clusters MW-17S/17D, MW-22S/22D, and MW-25S/25D. The third average on Table C-8 included all clusters in the second average plus well clusters MW-27S/27D, MW-28D/MW-19S, MW-29S/29D, MW-30S/30D, and MW-32S/32D.

With respect to Tables C-8 and C-9, it should be noted that most of the head differences are negative, indicating upward flow of ground water. In addition, the only times where significant positive averages occurred were during the March 2001 and March 2002 dates, which corresponded to the time of the prolonged drought experienced in New Jersey. Finally, the more wells that were incorporated into the shallow/deep average (see Tables C-8 and C-9), the lower the average value for a given date. All three (3) of these observations are consistent with the expected pattern of regional, vertical ground water flow discussed above and illustrated in Figure C-4.

To maintain consistency for comparison purposes between the various dates, only the second average difference is referred to in the flowing discussion of the ground water maps for the three most recent dates in the following sections. This was done to maintain consistency for comparison purposes between those dates.

1.7.1 March 4, 2002 Ground Water Flow Maps

Rainfall records for January and February 2002 from Newark International Airport totaled only 1.91 inches (NCDC 2003). Average precipitation for January and February 2002 for suburban northeast New Jersey is 6.52 inches with a standard deviation of 2.12 inches. Hence, the precipitation through the end of February was approximately 2.5 standard deviations below normal. In addition, a large rainfall event occurred at Newark airport the day before water levels were measured in March 2002.

Precipitation in the two (2) weeks prior to the water level collection date (March 4, 2002) was light up until March 3rd, when a large rainfall event (0.99 inches) was recorded at Newark International Airport (see Table C-3). Unfortunately, no records were maintained for Teterboro Airport on that date. As previously noted, recharge from rainfall will occur very rapidly in the shallow zone, but much more slowly in the deep zone.

The water levels obtained on March 4, 2002 were collected at the time of lower low tide; approximately 1½ days before the last quarter moon (see Table C-4). Therefore, the tidal range was at its minimum (3.5 to 4.5 feet in the Hackensack River at Hackensack, NJ). That specific change (higher high tide to lower low tide) would fall in the upper end of the spread of tidal range values. The estimated tidal change at the Arsynco site is therefore approximately a drop of 2 to 2.5 feet, assuming the semi-quantitative correlation developed between the Hackensack River gauging station and the site.

Shallow Zone Water Table – March 4, 2002

The March 4, 2002 water table map is illustrated in Figure C-6. The average ground water level in the shallow zone for this date was 5.39 feet above MSL. This is the highest of each of the three (3) dates of water level collection discussed herein. The high level observed in the shallow zone on March 4, 2002, occurring as it did during a major drought, indicates that recharge occurred quickly in the shallow zone following the previous day's precipitation. Shallow zone flow toward the south-southwest reflects drainage toward the tidal ditch at low tide. Based on the geology, the sediments to the south-southwest of the site are likely to be the highly permeable sediments of the glacial Lake Bayonne delta complex. The apparent ground water mound at MW-13S (indicating flow from the east to west) suggests accumulation of rainfall runoff and high recharge in that portion of the site. It may also reflect the influence of the previous high tide.

The influence of the former tidal channel along the northeast portion of the site (near well MW-4S) is demonstrated by the focusing of ground water flow from the west, towards well MW-4S.

Deep Zone Piezometric Surface – March 4, 2002

The March 4, 2002 piezometric surface map is provided as Figure C-9. The average water level in the deep zone for this date was 4.78 feet above MSL. This is the lowest level observed for each of the three (3) dates of water level collection discussed herein and reflects the state of site ground water due to the prolonged drought that occurred during 2001 through most of 2002. Flow toward the southwest in the deep zone (as observed on the west part of the property) reflects drainage at low tide toward the area where the glacial Lake Bayonne delta complex is closest to the surface.

Flow along the eastern part of the property is to the southeast. The lower hydraulic conductivity in the area of MW-10D results in lower rates of flow through that region.

The March 4, 2002 water levels also indicate that flow in the deep zone is onto the site from the north (i.e., onto the Arsynco property from the Cognis/Henkel property). This is the expected pattern based on analysis of the regional ground water flow discussed previously.

Vertical Gradients – March 4, 2002

Recharge will occur quickly in the shallow zone, but flow to the deep, D-well zone, will delay the impact of recharge events on the deep wells. Therefore, the precipitation record for this time period (large rainfall event the days before collection of water levels) explains the apparent anomalous reversal of hydraulic gradient at the MW-15S/15D cluster observed on March 4, 2002. The downward vertical gradient at the MW-15S/15D cluster at this time is explained by the long drought affecting both zones, combined with the rapid recharge to the shallow zone (from prior day's rainfall) and much slower recharge to the deep zone. The reversal back to an upward gradient at the MW-15S/15D cluster in the May 31, 2002 water levels supports this assessment, as noted below.

1.7.2 May 31, 2002 Ground Water Maps

A large amount of precipitation (1.62 inches) fell at the Newark International Airport in the two (2) weeks prior to May 31, 2002 (see Table C-3). The majority of that rainfall occurred 12, 13 and 14 days prior to measurement of the water levels in site wells. Again, precipitation records from Teterboro Airport were not available for the beginning part of the two (2) weeks prior to May 31st, when the highest amounts of precipitation fell at Newark. The impact that the rainfall had on the shallow water zone was minimal, as the recharge effect in the shallow zone had mostly dissipated during the time of the most significant rainfall and the collection of water levels. However, since the deep zone is expected to respond more slowly, the high precipitation at the beginning of the previous two-week period is likely to still be expressed in the deep (D-well), deeper (DD-well), zones.

Ground water measurements collected on May 31, 2002 were obtained at, or just before, the lower high tide stage and approximately 1¼ days before the last quarter moon (see Table C-4). The lower high tide stage occurring at the time of water level measurements implies that the tidal driving force would be expected to have been pushing water onto the site from the drainage ditches, with the estimated magnitude of the tidal change from the previous low being approximately 2 feet. The last quarter moon lunar phase would result in overall, less significant tidal fluctuations (3.5 to 4.5 feet in the Hackensack River at Hackensack, NJ).

Shallow Zone Water Table – May 31, 2002

The water table map for the shallow zone, created using the water levels obtained on May 31, 2002, is provided as Figure C-7. The average water level for the shallow zone for this date was 4.48 feet above MSL. This is the lowest of each of the three (3) dates of water level collection discussed herein, and reflects a combination of the prolonged drought conditions and the relatively large amount of time between the rainfall events which occurred nearly two (2) weeks prior to May 31st. This time allowed the recharge water to drain out of the shallow zone.

As Figure C-7 indicates, water was coming onto the site from the area of the railroad tracks located to the west of the site. However, the influx of water from the west was not sufficient to overcome the high head at the MW-15S/15D well cluster. This is likely the result of a combination of factors, including the minimal tidal influence that occurs at the northwest corner of the site, particularly at times when the tidal range is at its lowest (e.g., near last quarter moon and at the lower high tide stage). In addition, since the vertical gradient at the MW-15S/15D cluster is upward a higher hydraulic head at this location would be expected. Water levels at well MW-15S may also be affected (i.e., maintained) by an historic spring near that location, as discussed previously.

The high tide has the effect of muting the focus of ground water flow into the former tidal drainage ditch that was present along the northeast site boundary near well MW-4S. Flow along the northwest boundary of the Arsynco site is again from the north, onto the Arsynco property from the Cognis/Henkel property near Henkel well MW-17.

Deep Zone Piezometric Surface – May 31, 2002

The piezometric surface map for deep groundwater, created using the water levels obtained on May 31, 2002, is provided as Figure C-10. The average water level in the deep zone for this date was 4.95 feet above MSL. This is an intermediate value for each of the three (3) dates of water level collection discussed herein. The increased, average water level from the March 4, 2002 date is a result of the large recharge event that occurred 12-14 days prior to May 31, 2002. This is consistent with the discussion above regarding the relative timing of when recharge occurs in the deep versus shallow ground water zones.

As indicated on Figure C-10, groundwater flow in the deep zone on May 31, 2002 is onto the Arsynco site from the west, northwest and southwest. Ground water flow from the west and northwest onto the site is consistent with the regional pattern of ground water flow discussed previously, and which is illustrated in Figure C-4. The flow of ground water onto the site from the southwest reflects the recent recharge event compounded by the high tidal stage which influences the groundwater in the shallow areas of the deltaic deposits to the west and southwest, where there is no confining layer separating a "shallow" from a "deep" groundwater zone.

Groundwater flow on the eastern part of the site is to the east-southeast in the area north of MW-10D, with a stronger south-southeast component of flow to the south of well MW-10D.

Groundwater flow along the northern boundary of the Arsynco site is from the northwest, onto the Arsynco site from the area of Cognis/Henkel well MW-17. This pattern is expected based on the analysis of regional ground water flow. The same water level elevations for wells MW-8D and MW-14D clearly depict the northwest to southeast flow pattern in this area.

Vertical Gradients – May 31, 2002

The average, vertical head difference between shallow and deep zones on May 31, 2002 was -0.43 feet, indicating an upward gradient and, therefore, an upward ground water flow. This is consistent with the regional analysis of vertical ground water flow discussed above and illustrated in Figure C-4. The combination of recharge reaching the deep groundwater zone and time for recharge to have already drained from the shallow zone during this extended period of drought explains the vertical gradient change from the March 4, 2002 date back to upward flow.

1.7.3 May 19, 2003 Ground Water Maps

As shown on Table C-3, six (6) days of rainfall were recorded at Newark International Airport during the two-weeks prior to May 19, 2003, with total precipitation of 0.54 inches during that time. The majority of the total rainfall (0.37 inches) occurred on May 8th, eleven days prior to collection of the water level measurements. No rainfall amounts were recorded for the six (6) days immediately preceding the May 19, 2003. The precipitation records for Teterboro Airport during the same period were very similar, totaling 0.53 inches of rainfall. Again, the majority of the total rainfall at Teterboro (0.38 inches) fell on May 8th, eleven days prior to collection of the water level measurements. A very minor rainfall event (0.01 inches) was recorded at Teterboro on May 17th, two (2) days prior to collecting the water level data from site wells.

The impacts of the precipitation events in the 2 weeks leading up to May 19, 2003 are expected to be similar to those discussed in relation to the May 31, 2002 water level event. Specifically, with no significant rainfall for approximately 11 days, the effect of recharge in the shallow zone would be expected to have largely dissipated by the time that water levels were obtained on May 19, 2003. The effect on recharge of the deep zone would be expected to be less significant than that experienced on the May 20002 date, although it would likely be near the maximum influence for that specific recharge event. Overall, the rainfall recharge influence on groundwater observed on May 19, 2003 would be expected to be less significant than the influence observed in May 2002, since the total rainfall was only about one third of the May 2002 time.

The May 19, 2003 water levels were collected at approximately the mid-point between the lower low tide and the lower high tide stages and approximately 3½ days before the full moon (see

Table C-4). Therefore, the tidal range was approaching its maximum values, and the tidal range in the Hackensack River at Hackensack, NJ is estimated to have been between 6.2 and 8.1 feet at that time. The specific change between the lower low tide and the lower high tide is estimated to be approximately 6.4 feet. Therefore, collection of water levels from site wells at the midpoint in this tidal cycle would suggest an increase in tide height of approximately 3.0 to 3.6 feet. Translated to the Arsynco site, the change of water levels in the ditches is estimated to have been on the order of 1.5 to 2 feet.

Shallow Zone Water Table – May 19, 2003

The water table map for the shallow zone, created using the water levels obtained on May 19, 2003, is provided as Figure C-9. The average water level for the shallow zone for this date was 4.87 feet above MSL. This is the intermediate value of each of the three (3) dates of water level collection discussed herein, and reflects the beginning of the end of the regional drought. Based on the lunar stage at the time of water level measurements, large tidal ranges would be expected for the site. However, with the water level collection time falling at the midpoint of a tidal cycle, the water levels in the drainage ditches surrounding the site would not be expected to have reached their maximum value.

As Figure C-9 indicates, shallow zone water was coming onto the site from the northwest, south of MW-28D. This reflects the approaching high tide stage. The high water level recorded in well MW-15S is interpreted to be the expression of upward flow from a former spring near that location. The focusing of ground water flow into the former tidal stream/ditch is apparent near MW-15S through the wrapping of the ground water contours around well MW-29S. Similar to the May 31, 2002 map, ground water flow on the western half of the site is focused toward the south, along the line of 13th Street.

Deep Zone Piezometric Surface – May 19, 2003

The piezometric surface map for deep groundwater, created using the water levels obtained on May 19, 2003, is provided as Figure C-11. The average water level in the deep zone for this date was 5.20 feet above MSL. This is the highest level for each of the three (3) dates of water level collection discussed herein and reflects continuing recharge of the deep zone as ground water recovers from the prolonged drought of 2001-2002.

The highest water level observed in the deep zone wells on May 19, 2003 was at well MW-15D. This reflects recharge coming onto the site from the north and northwest, as suggested by the regional ground water flow pattern discussed previously and illustrated in Figure C-5. This focusing of ground water flow is the likely source of the natural spring reported to have existed near the location of the MW-15S/15D well cluster. The steep hydraulic gradients between MW-15D and wells MW-8D and MW-29D are consistent with the interpretation that a natural spring was formerly located near that area.

The May 19, 2003 water level collection event utilized several new, off-site wells installed to the west, north and southeast of the Arsynco site. The inclusion of these additional well locations was helpful in defining two (2) major pathways of ground water flow in the deep zone at the

Arsynco site. Both of the major flow pathways essentially run from west to east across the site and are divided along a line running approximately from the west and the area of off-site well MW-27D along the line of MW-16D, MW-5D, and MW-10D, toward well MW-25D. The lower hydraulic conductivity measured at MW-10D is consistent with the observed ground water flow pathways. The divide between flow to the north and south of that location remains present. The pathway observed to the north of the stated division line is shown to run from the approximate location of well MW-18D toward MW-8D, where the pathway is diverted toward the east, directing flow toward MW-22D, MW-11D, and MW-9D. The pathway observed to the south of the stated division line is shown to extend from well MW-17D, passing through the area encompassed by wells MW-13D, MW-12D, and MW-25D.

The southern pathway of groundwater flow in the deep zone is consistent with the regional flow analysis discussed previously, and illustrated on Figure C-5. Ground water flow is apparently focused through one of the major lobes of the glacial Lake Bayonne delta complex. The historical topographic maps and the geologic interpretation discussed above are consistent with this understanding. The geologic log of well MW-6D and the apparent thinning of the glacial Lake Bayonne delta to the north at wells MW-17D and MW-16D is consistent with this interpretation (i.e., that the southern part of the site overlies the northern edge of a major sub-lobe of the delta complex). This is illustrated schematically on Figure B-16 of Geologic CSM.

The northern pathway of groundwater flow in the deep zone is likely to have been formed in a different geologic fashion. It is interpreted to have resulted from deposition of alluvial sands in stream channels that were eroded into the glacial lake bottom deposits during the long, subaerial exposure of those sediments (Stanford and Harper 1991; see discussion of geologic history above in Section 4.4).

Vertical Gradients – May 19, 2003

The average, vertical difference in head between the shallow and deep zones for this date was -0.20 feet. Once again, this is consistent with the assessment of regional, vertical ground water flow discussed previously and illustrated in Figure C-4. The intermediate nature of this average gradient among the three dates reflects the lower precipitation occurring during the two weeks prior to May 19, 2003.

HYDROGEOLOGIC CSM (2013 UPDATE)

2.0 HYDROGEOLOGY

The conceptual model for the hydrogeology of the Arsynco Site was developed in detail in JMC (2003). The model was based on a thorough literature review and extensive Site hydrogeologic data. Subsequent investigations have been consistent with that conceptual model. The following subsections provide significant, supplementary material to update and aid understanding of the hydrogeologic CSM provided in JMC (2003).

2.1 Regional Groundwater Flow

Regional patterns of groundwater flow are governed by large-scale hydrogeologic boundaries. These boundaries are generally dictated by the regional topography and the location and orientation of regionally important streams (Fetter 1994).

Vertical Regional Groundwater Flow

The expected regional pattern of groundwater flow near the Arsynco Site is illustrated in the cross-section in Figure C-4. The low-lying sediments of the Meadowlands act as a discharge zone drained by the Hackensack River and its tidally-influenced tributaries. A strong upward component of flow is expected emerging from the fractured bedrock of the Passaic Formation underlying the highlands just west of the Arsynco Site. Strong upward flow is expected through the coarse glacial lake delta sediments. This upward flow is impeded significantly by the S-D confining zone and its off-site equivalents along the western margin of the Site. Therefore, the S-D confining zone is expected to direct flow horizontally through the deep groundwater zone where the upward flow is impeded.

Horizontal Regional Groundwater Flow

The expected regional pattern of ground water flow in map-view near the Arsynco Site is illustrated in Figure C-5. This interpretation is based on the topography, geology, and surface water distribution. The historical influence of the design and operation of the pond on the nearby Henkel/Cognis property and the current influence of the Henkel/Cognis slurry wall is illustrated by the deflection of groundwater flow to the south onto the Arsynco property. Horizontal flow is directed through the coarser sediments of the glacial lake delta complex and the shallow fill sediments. This horizontal flow continues, although significantly slowed, as the groundwater passes from the coarser delta topset and foreset beds into the bottomset beds of the glacial delta complex toe and on into the varved silts and clays of the glacial lake bottom deposits. Local deviations from these regional patterns of flow are expected due to heterogeneities of the subsurface sediments and more detailed distribution of tidal drainage ditches than are noted in these figures.

Local patterns of groundwater flow in the deep groundwater zone are governed by local boundary conditions and the heterogeneous distribution of horizontal hydraulic conductivity. These local conditions are discussed in greater detail in section 3.5.3.

2.2 Hydrostratigraphy

Three (3) groundwater zones and two (2) confining zones have been identified in the subsurface at the Arsynco Site. The deepest groundwater zone (the "DD" groundwater zone) is characterized by the DD-well series on the Arsynco Site (triple cased wells MW-5DD and MW-11DD). Wells MW-5DD and MW-11DD are set at virtually identical depths (screened zone intervals cover the elevation range of approximately -45 to -35 feet). The DD-groundwater zone consists of the sandy sediments of the lacustrine fan deposits (Q_{bnf}) formed within Glacial Lake Bayonne. The cross-sectional geometry of this unit in the area of the Arsynco Site is complex (see Figure B-3 in Geologic CSM). MW-5DD is set in the lacustrine fan deposits (see Figure B-3 in Geologic CSM). However, MW-11DD appears to be set in the glacial lake bottom sediments of Glacial Lake Bayonne, where this unit thickens to the north of the lacustrine fan deposit (see Figure B-3 in Geologic CSM). Hence, MW-11DD is set in the next overlying unit, the D-DD confining zone.

Overlying the DD-groundwater zone are the varved silts and clays of the Glacial Lake Bayonne lake bottom sediments (Q_{bnl}) which form the D-DD confining zone at the Arsynco Site. In many areas of the region, the two (2) formations pass seamlessly from the older Glacial Lake Bayonne lake bottom sediments into the lake bottom of the more recent stage of Glacial Lake Hackensack. Sediments of the D-DD confining zone are in turn overlain by the glacial lake delta complex (Q_{bn}). These consist of coarse to medium and fine sands with silt and clay layers. The delta grades laterally toward the east, merging with the Glacial Lake Bayonne lake bottom sediments (Q_{bnl}). This comprises the deep or "D" groundwater zone at the Site. This is the zone of deep groundwater at the Arsynco Site that will require remediation and that is the subject of the RAW contained herein. Wells screened in this zone are referred to a the D-well series on the Arsynco Site. East of the deltaic transition zone illustrated in Figure B-10 of the Geologic CSM, the deep groundwater zone is defined vertically in an operational sense by the tops and bottoms of important wells monitoring this zone. In particular, the top of the deep groundwater zone is set at an elevation of -9.0 feet NAVD88 based on the top of the screened zone of well MW-22D. The bottom of the deep groundwater zone is set at -25.0 feet NAVD88 based on the bottom of the screened zone of well MW-9D. The rationale for this operational definition is the apparent convergence of vertical groundwater flow into this zone, which is discussed below.

Overlying the D-groundwater zone are varved silts and clays of the Glacial Lake Hackensack lake bottom sediments (Q_{hkl}) and the silts and clays of the later salt marsh deposit with a peat layer at the top (Q_m). The peat layer has been termed the Meadow Mat. These sediments comprise the S-D confining zone.

The topmost hydrostratigraphic unit is the shallow groundwater zone, which is comprised of the surface deposits. The surface deposits consist of artificial fill of varying hydraulic conductivity. These sediments form the shallow groundwater zone and are characterized by the shallow or "S"-series of wells.

Killam Associates (1991a) prepared a geologic and hydrogeologic interpretation for the Cosan Chemical site that lies just to the south of the Arsynco Site. Boring logs from the Cosan wells and hydraulic conductivity measurements from those wells are consistent with the geologic and hydrogeologic interpretation presented above.

2.3 Site Groundwater Flow

2.3.1 Shallow Groundwater Zone

Groundwater flow in the shallow groundwater zone plays an important role in understanding groundwater flow in the deep groundwater zone. The details of this link are discussed in this section.

Groundwater flow in the shallow groundwater zone is governed principally by the distribution and orientation of the tidal drainage ditches which form the hydrologic boundaries for this zone. The Arsynco Site is virtually surrounded by these drainage ditches, with the exception of a short stretch of the north property line along the western edge of the property that borders the Henkel/Cognis site just north of Arsynco, although an old, buried ditch did once exist in this area. The historical shallow groundwater zone maps indicate that groundwater flows onto the Arsynco Site from the north along this stretch of the property boundary. This is consistent with the fact that as part of their remediation, Henkel/Cognis constructed a vertical slurry wall to assist their capture of contaminated groundwater flowing east from their site. It is also consistent with the historical operation and design of the Henkel/Cognis pond that was used for plant operations. The placement and construction of the Henkel/Cognis pump-and-treat system mechanisms, including the slurry wall, is not sufficient to capture the shallow groundwater from that border region (southwest portion of Henkel/Cognis site and northwest portion of Arsynco Site).

The influence of tidal cycles in the tidal drainage ditches and of precipitation events on groundwater flow in the shallow groundwater zone was studied in detail during a tidal study and pumping test conducted in June 2011 (see Section 6.1.2 of 2013 RAW). Tidal flow associated with the tidal drainage ditches plays a very strong role in groundwater flow at the Arsynco Site in both the shallow and deep groundwater zones. A detailed analysis of shallow groundwater flow patterns, temperature variations, and the influence of precipitation observed during the June 2011 study were provided in Appendix E of the 2013 RAW. The thin, shallow character of the shallow groundwater zone makes precipitation events highly influential, especially when precipitation occurs with times of larger tidal cycles. The role of tidal influences observed during the June 2011 tidal study on the shallow groundwater zone was also discussed and illustrated in Appendix E of the 2013 RAW. The effects of the tidal cycles on groundwater flow in the shallow zone have largely prevented the significant migration of VOC contaminants present in shallow groundwater. Significant buildup of groundwater occurs in the shallow groundwater zone along the tidal drainage ditches during the periods of greatest tidal range. This buildup of groundwater in the shallow zone plays a major influence on the overall short-term and long-term behavior of groundwater in the deep groundwater zone.

2.3.2 Deep Groundwater Zone

Hydraulic Head in the Deep Groundwater Zone

Hydraulic head at a given location in the deep groundwater zone is measured by the water level in a well. A refined, theoretical treatment of head in a confined zone that is applicable to the Arsynco Site were presented in Appendix E of the 2013 RAW. In short, head is a combination of the vertical stress due to the weight of overlying materials (atmosphere, water, and sediment) and a horizontally transmitted hydraulic pressure from unconfined hydraulic source areas exposed to the atmosphere. In the case of the Arsynco Site, the hydraulic source area is the area of exposed deltaic sediments west of the Site and east of the highlands areas.

Deep groundwater zone water levels were examined in detail during the June 2011 Tidal Study and Pumping Test (see Section 6.1.2 of 2013 RAW). Wells were divided into two (2) groups based on their general response pattern: those that are tidally influenced, and interior Site wells that experience little or no discernible tidal fluctuation. Strongly tidally-influenced wells included MW-9D, MW-10D, and MW-25D. Wells expected to behave similarly (i.e. - likely to have strong tidal influence), but which were not included in the 2011 study, include MW-4D, MW-12D, and MW-32D. Wells MW-14D and MW-34D experience moderate tidal influence, with the highest tides being clearly registered but lower tides not as strongly apparent.

Interior Site wells were most strongly influenced by precipitation events. The shallow groundwater zone at the Arsynco Site, located in the shallow fill materials, is very thin. Significant variations in the saturated thickness occurred in response to rainfall. This response is transmitted virtually instantaneously to the deep groundwater zone via the change in effective stress.

The influence of precipitation events on the horizontally transmitted component of the hydraulic head takes time to propagate through the system from the hydraulic source, the subaerially exposed sediments of the Glacial Lake Bayonne delta, west of the Site. Infiltration into those sediments requires more time due to the greater effective thickness of the vadose zone. The resulting pressure wave following a large precipitation event then takes time to propagate through the deep groundwater zone from west to east through the lower hydraulic conductivity sediments that lie in and east of the delta transition zone (see Figure B-10 of Geologic CSM).

Groundwater Flow in the Deep Groundwater Zone

The general pattern of groundwater flow in the deep groundwater zone is from the west toward the east or southeast, consistent with the regional flow pattern illustrated in Figure C-5. Groundwater flows onto the Site from the northwest, and there is a strong upward gradient in the deep zone, particularly in the area of MW-15D. The vertical gradients and flow are discussed in greater detail below.

Groundwater flow in the southwest portion of the Arsynco Site reveals a strong tidal influence. There is a general pattern of flow toward the south-southeast to south along the western margin, with groundwater in the deep zone then refracting toward the east in the area between wells

MW16D, MW-17D, and MW-6D. This is interpreted to reflect the influence of the transition zone of the delta where the coarser sediments of the glacial delta complex transition steeply into the finer-grained, less permeable sediments of the delta toe and glacial lake bottom sediments (see Geologic CSM and Figure B-10 of Geologic CSM). There is a convergence of groundwater flow in the area of MW-17D, with groundwater flowing toward MW-17D from both the north and from the south. This has been consistent (see the multiple groundwater flow maps for the deep groundwater zone that are included in the multiple Arsynco reports). Flow then refracts toward the east and southeast from the area of MW-17D as groundwater enters the delta toe and varved lake bottom sediments.

Groundwater flow in the southeast portion of the Site is consistently toward the southeast to south-southeast. This is interpreted to reflect the hydraulic conductivity distribution associated with the lobate structure of the delta complex and its transition into delta toe and glacial lake bottom deposits; the delta complex extends slightly farther toward the east, along the southern edge of the Arsynco Site, and groundwater flows preferentially through the more permeable sediments (see Figures B-1, B-10 in Geologic CSM and Figure C-5 of Hydogeologic CSM).

Groundwater flow in the northwest portion of the Site reflects a combination of the generally higher water levels off-site to the north and west of the Site and the influence of the delta transition zone (Figure B-10 Geologic CSM). The transition zone, through its large reduction in hydraulic conductivity, causes the steep hydraulic gradients that are regularly present between well MW-15D and wells MW-29D and MW-8D. Groundwater flow direction is also refracted toward the east as it enters the lower hydraulic conductivity sediments of the delta toe and glacial lake-bottom deposits. The general southerly flow along the western margin of the Site roughly parallels the delta transition zone (e.g. - flow from MW-15D toward MW-16D), as illustrated on Figure B-10 (Geologic CSM) and in historic groundwater flow maps.

Groundwater flow in the northeast portion of the Site is complex. This complexity is important to understand, as it plays a major role in the transport behavior of contamination in the most contaminated area of the D-zone aquifer (the area encompassing wells MW-11D, MW-22D, and MW-38D). This area is strongly influenced by tidal fluctuations, experiencing regular, periodic flow-direction reversals where the "normal," general west-to-east flow is interrupted for periods of time, resulting in groundwater flow converging into the area around MW-11D. The tidal influence in the deep groundwater zone arises through loading in the shallow groundwater zone. This is discussed in detail in Appendix E of the 2013 RAW. The historical reversals and groundwater flow variation in the region bounded by wells MW-11D, MW-9D, and MW-10D were examined in detail. The historical analysis indicates that if water levels are measured at any random time, at least 28% of the time groundwater flow is reversed from the "normal," general west-to-east flow pattern, which results in a depression of the piezometric head in the area of well MW-11D. This flow reversal is interpreted to result from the fact that the area around MW-11D is surrounded fairly closely on three (3) sides by existing and former tidal ditches, creating a U-shaped region bounded by tidal ditches on Tract 2 to the east, and former and existing tidal ditches along the north and south property borders. The entire 17-day time during the June 2011 tidal study (Section 6.1.2 of 2013 RAW) was a period of this "reversed" flow direction in the deep groundwater zone. Appendix E of the 2013 RAW provides a more detailed evaluation of the entire June 2011 study period. The analysis demonstrates that this reversal of flow in the deep groundwater zone is a common occurrence that can be present at least 25% of the time. This analysis indicates the extreme nature of the hydraulic complexity, with groundwater flow direction swinging back-and-forth as much as 100° in response to the tide cycles. The hydraulic gradient is also highly variable, increasing and falling by a factor of 6 or 7 during the time of the largest tidal range.

2.3.3 *DD Groundwater Zone*

As noted above, patterns of groundwater flow are governed principally by the location and orientation of hydrologic boundaries. At the local scale of the Arsynco Site, the hydrologic boundaries are subtly different for the different hydrostratigraphic units. The boundaries for the DD groundwater zone are more regional in nature. No definitive groundwater flow direction in the DD groundwater zone can be determined since only two (2) wells are available to measure water levels in this zone (MW-5DD and MW-11DD) and one of those wells (MW-11DD) has been interpreted to be screened in the D-DD confining zone. Historically, water levels have generally been higher in MW-11DD than in MW-5DD, suggesting a general north-to-south flow direction oriented roughly parallel to the Hackensack River.

2.3.4 *Vertical Groundwater Flow*

Vertical groundwater flow across the S-D confining zone and across the D-DD confining zone are discussed in this section. The expected pattern of regional vertical groundwater flow is upward, reflecting the Hackensack River Valley as a regional groundwater discharge zone. This is illustrated in Figure C-4.

Historical values for the vertical hydraulic gradient across the S-D and D-DD confining zones are provided for several well combinations in Tables CT-10 through CT-12. Gradients for the following well combinations provide data to evaluate vertical groundwater flow along the western margin of the Arsynco Site: MW-15S/MW-15D (15S/D), MW-27S/MW-27D (27S/D), MW-19S/MW18D (19S/18D), MW-19S/MW-28D (19S/28D), and MW-17S/MW-17D (17S/D). The historical, vertical flow data for this group of wells is presented in Table CT-10.

Three (3) combinations of wells were used to examine vertical groundwater flow across the S-D confining zone in the central portion of the Site: MW-5S/MW-5D (5S/D), MW-11S/MW-11D (11S/D), and MW-22S/MW-22D (22S/D). Historical data for this set of wells is presented in Table CT-11.

Two (2) well combinations are available to examine vertical groundwater flow across or through the D-DD confining zone: MW-5D/MW-5DD (5D/DD) and MW-11D/MW-11DD (11D/DD). The latter combination, 11D/DD, does not truly cross the D-DD confining zone, but does provide an estimate for vertical groundwater flow through the glacial lake bottom sediments of the deeper portions of the Site. Historical data for vertical flow through the D-DD confining zone are presented in Table CT-12.

A range of vertical hydraulic conductivity values, K_v, was determined using data from the June 2011 Tidal Study and Pumping Test. The estimated range of K_v values was 2.85×10^{-5} ft/day to

2.85×10^{-3} ft/day. These value were used to estimate the minimum and maximum specific vertical discharge rates in units of ft^3/ft^2/day. The "likely" estimate was made assuming a vertical hydraulic conductivity value of $K_v = 2.85 \times 10^{-4}$ ft/day. Estimates for the total vertical groundwater flow in units of gallons per day (gal/day) were made from the specific discharge values through an area with a radius of 50 ft (7,854 ft^2). Please refer to Appendix E of the 2013 RAW.

Flow Across the D-DD Confining Zone

Historical hydraulic gradient data for vertical groundwater flow through the D-DD confining zone are presented in Table BT-3 in Appendix B of the 2013 RAW. These historical gradients are illustrated graphically in Figure C-71. It should be noted that in the geological and hydrostratigraphical interpretation, wells MW-11D and MW-11DD are both screened in the same hydrostratigraphic unit. MW-11DD was installed in the Glacial Lake Bayonne bottom deposits in a thickening of those sediments that begins at and continues to the north of the Site. MW-11D is screened in the toe of the Glacial Lake Bayonne delta complex where the sediments grade into the glacial lake bottom. MW-5DD is located in the Glacial Lake Bayonne lacustrine fan deposits that comprise the hydrostratigraphic DD-well groundwater zone. Therefore, gradients measured in the MW-11D/MW-11DD well pair are a measure of the hydraulic gradient within the thickening D-DD confining zone. Gradients measured in the MW-5D/MW-5DD well pair provide a measure of the gradient between the deep (D-well) groundwater zone and the DD-well groundwater zone (i.e. - across the full D-DD confining zone in that location).

The dominant vertical groundwater flow is upward in the D-DD confining zone. Again, this is consistent with the expected regional cross-sectional pattern of flow near the Site. The first two (2) measurements at the 5D/DD well pair (see Table CT-12) indicate downward vertical flow (positive gradient). These measurements were made in March and May 2002, in the middle of a prolonged drought that extended from October 2000 through early 2003. The downward gradient is interpreted to have resulted from reduced upward flow out of the adjacent highlands to the west of the Site due to the drought. The single downward measure in the 11D/DD pair in May 2004 (see Table CT-12) is interpreted to be a delayed hydrologic response to the drought moving through the tighter sediments of the lake-bottom deposits.

The hydraulic gradient and flow through the D-DD confining zone responds much more slowly than flow through the S-D confining zone. This can be observed by comparing the hydraulic gradient within the D-DD confining zone in well pair 11D/DD during the June 2011 tidal study and pumping test (see Figure C-72) with the vertical flow through the S-D confining zone during the same test (see Figure C-73).

Flow Across the S-D Confining Zone

Historical hydraulic gradients for well groups along the western margin of the Site generally indicate upward vertical groundwater flow across the S-D confining zone (see Table CT-10). These data are illustrated graphically in Figure C-74. This is consistent with the expected regional pattern of groundwater flow. Only six (6) measurements out of a total of 51 observations indicated downward vertical flow, and three (3) of those are from the

MW-19S/MW-18D group, which are likely to have less negative results because of the larger spatial separation between those wells (not clustered) and the patterns of horizontal flow within the shallow and deep groundwater zones. The historical, average hydraulic gradients are all negative (Table CT-10), indicating upward vertical groundwater flow. The rate of vertical flow is low, however, due to the low vertical hydraulic conductivity through the S-D confining zone sediments. Total, estimated flow rates through areas of 50-feet radius around the well groups range between approximately 0.07 and 32 gallons per day, with a more likely range of between 0.7 and 3.2 gallons per day (Table CT-10).

Historical data for vertical groundwater flow from well groups near the center of the Site are presented in Table CT-11. The historical gradients are illustrated graphically in Figure C-75. Vertical groundwater flow in this area is predominantly downward across the S-D confining zone. The historical, average total vertical flow rates through a 50-feet radius area are very low, with the estimates ranging between 0.004 and 2.6 gallons per day. This reflects the combination of a thick S-D confining zone and modest head differences, resulting in low magnitude hydraulic gradients combined with the low vertical hydraulic conductivity of the S-D confining zone. Vertical flow through the central areas of the Site can quickly flip back and forth between downward and upward in response to precipitation influences at the center-site wells and tidal influences near the tidal drainage ditches. This is apparent in hydraulic gradient results measured during the June 2011 tidal study and pumping test (see Section 6.1.2 of 2013 RAW). These results are illustrated in Figure C-73, where the influence of the large precipitation events (E_{j6}, E_{j6a}, and E_{j9}) is clearly apparent for most of the well groups. The tidal influence is shown clearly at well cluster 25S/D, and at times of highest tides in the 14S/D and 34S/D groups.

Summary of Vertical Groundwater Flow

Upward vertical flow prevails over the western portion of the Site and across the D-DD confining zone in the central part of the Site. This is consistent with the regional groundwater flow analysis. Vertical flow across the S-D confining zone near the center of the Site and along the tidal drainage ditches is highly variable, with the influence of precipitation strongly influencing levels in the shallow zone, and tides influencing water levels in both the shallow and deep zones near the tidal drainage ditches.

Vertical flow in the region of wells MW-11D, MW-22D, and MW-38D appears to converge on the deep groundwater zone, with predominant downward flow across the S-D confining zone and upward flow through the D-DD confining zone. However, the vertical groundwater flow rates are very low because of the low vertical hydraulic conductivity.

Figure C-1. Detail from the 1901 topographic map of Wilson. The area near Carlstadt and Rutherford is labeled "Boiling Springs", indicating upward hydraulic gradients. This supports the regional cross-sectional analysis of ground water flow. Note also the possible delta lobe extending into the swamp-land between Broad St. and Division, similar to the 1884 map (Figure C-2).

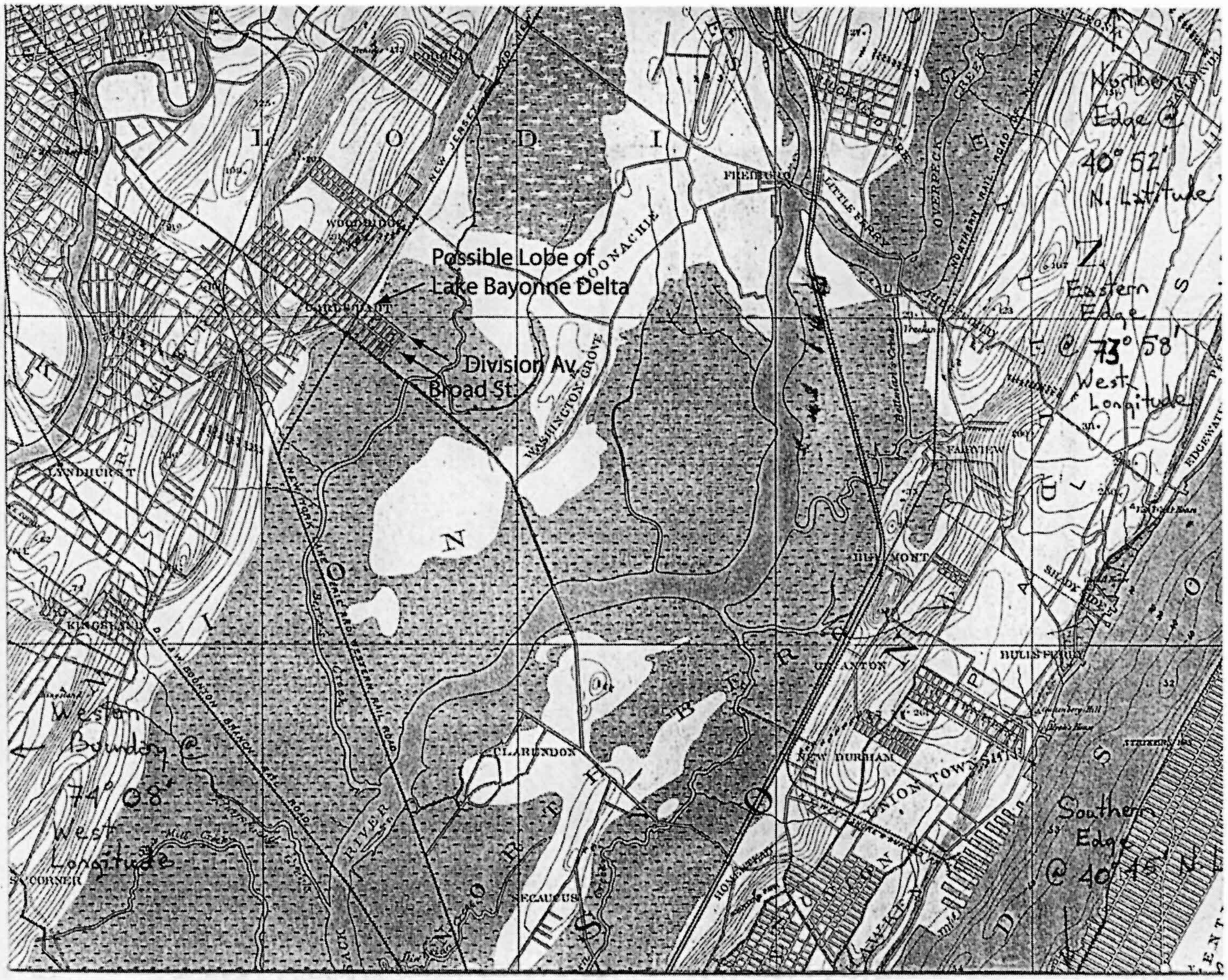


Figure C-2 Detail from the 1884 topographic map of Cook, Smock, and Vermeule. Note apparent construction of Broad St. and Division Avenues with NE-SW trending numbered streets extending into the swamp area. Note also the possible lobe of the glacial Lake Bayonne delta centered approximately on Division Avenue.

Figure C-3 Detail from the 1896 topographic map of Smock and Vermeule. Note labeling of Rutherford area and swamp-land as "Boiling Springs", supporting the regional flow analysis indicating upward flow in the lowlands. Note also the possible delta lobe between Broad St. and Division Avenue, similar to 1884 map (see Figure C-2).

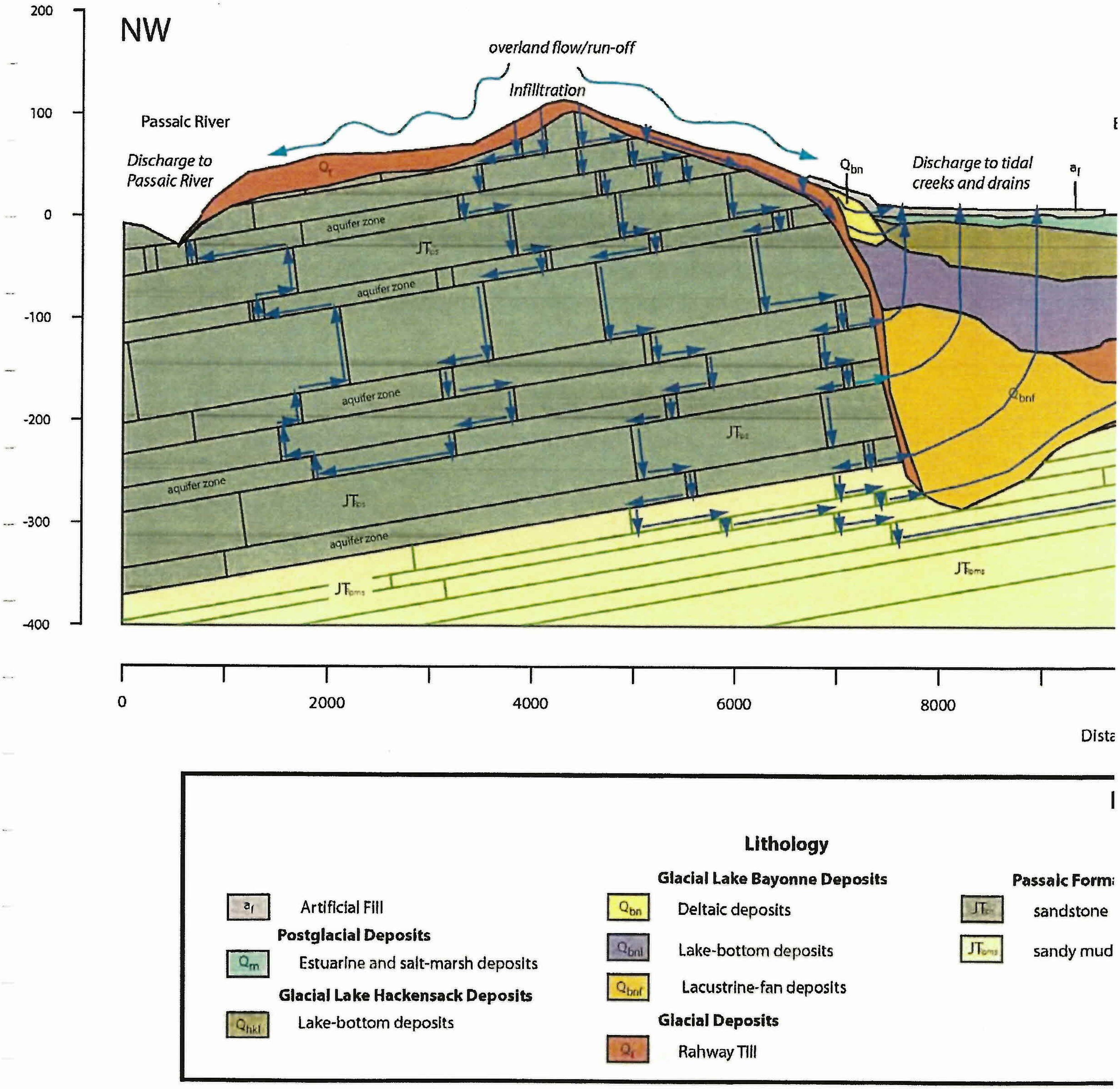
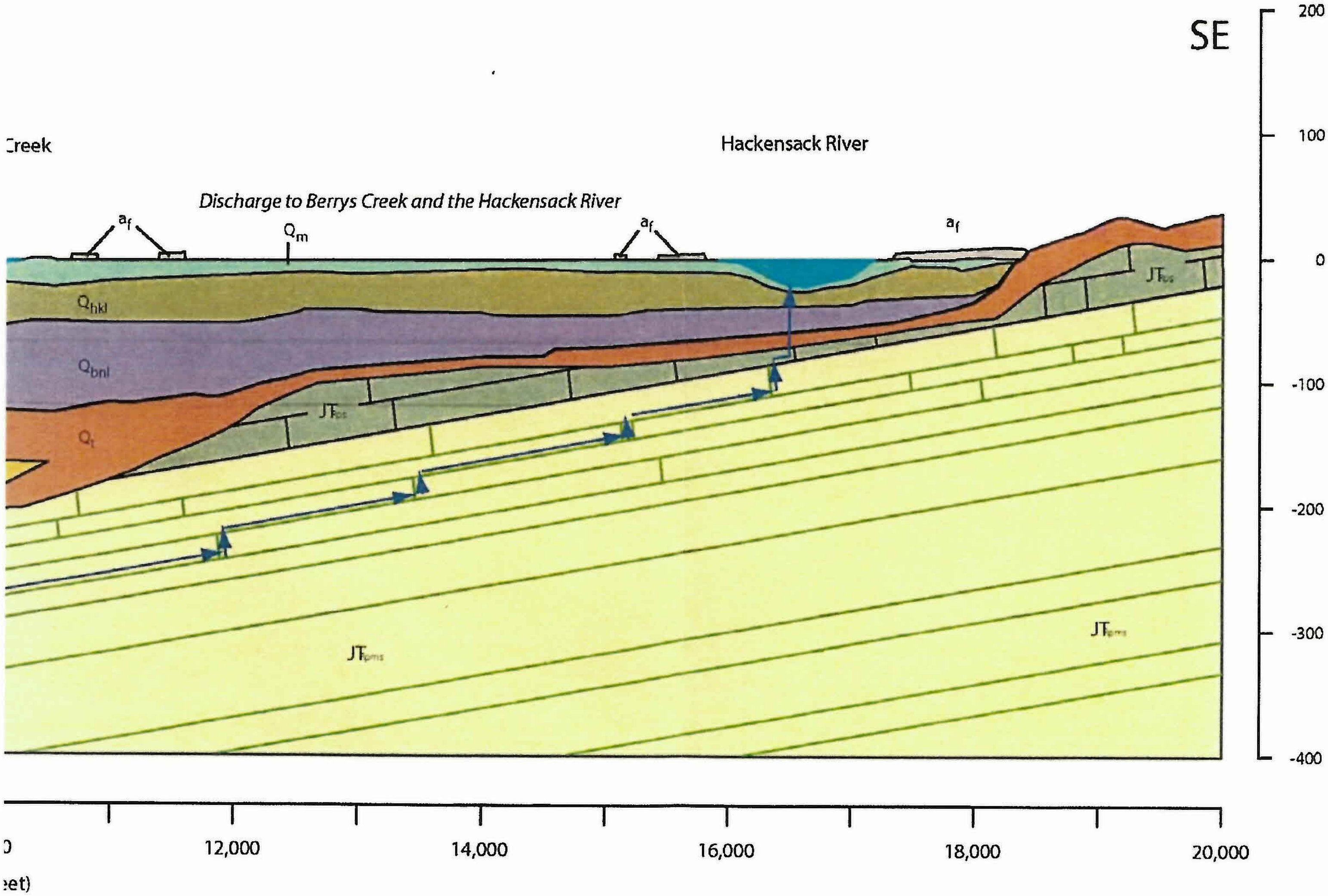


Figure C-4 Cross-section illustrating expectded pattern of regional ground water flow near the



nd

Lower Jurassic and Upper Triassic)

Other Symbols

Fractured or jointed bed of JTr_{ps}

Fractured or jointed bed of JTr_{pms}

Ground water flow path

Overland flow/runoff

River or stream

Geology Sources

Quaternary units from Stanford (1993)

Bedrock units from Avery et al. (1996)

Vertical Exageration = x10

nco, Inc. site.

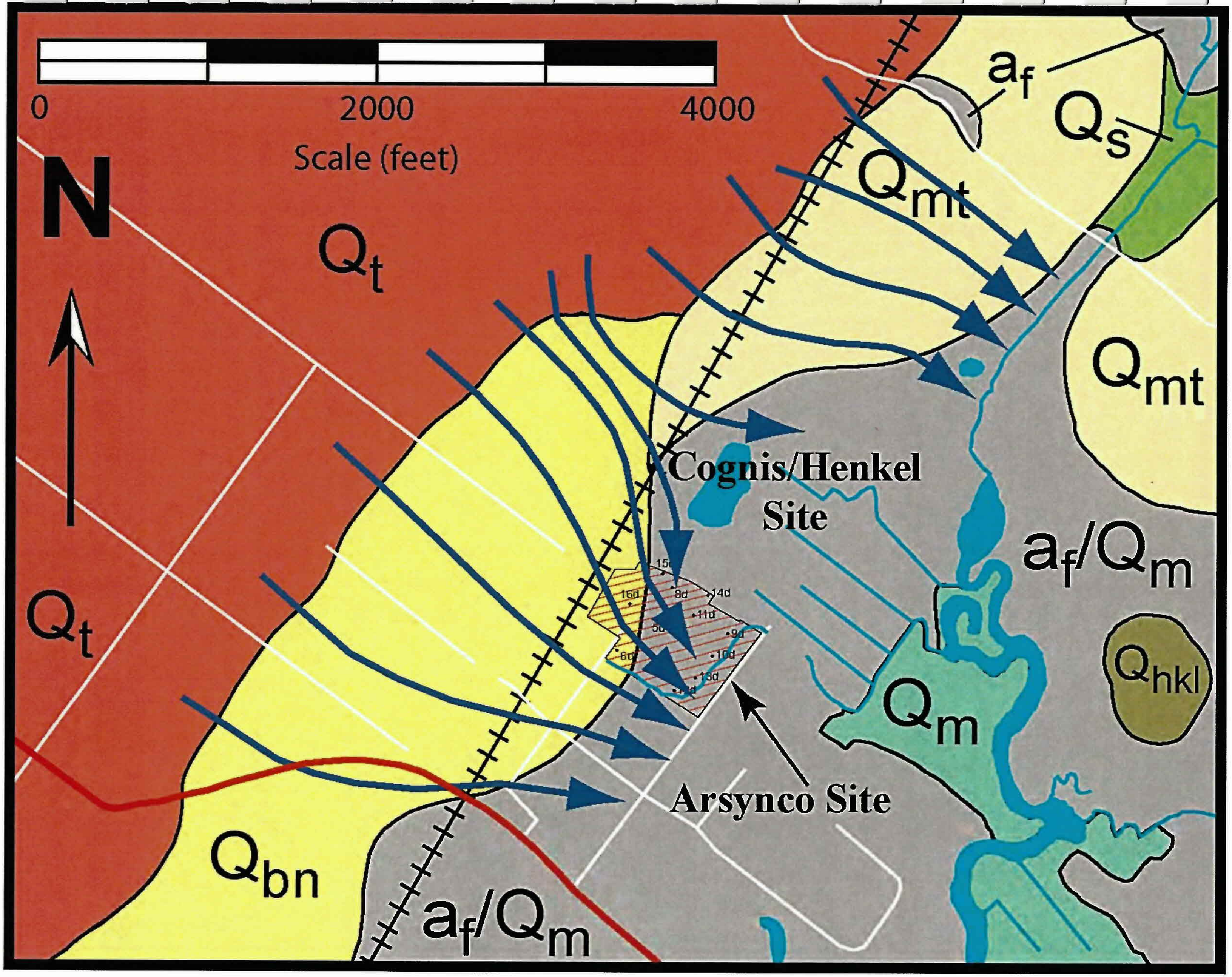
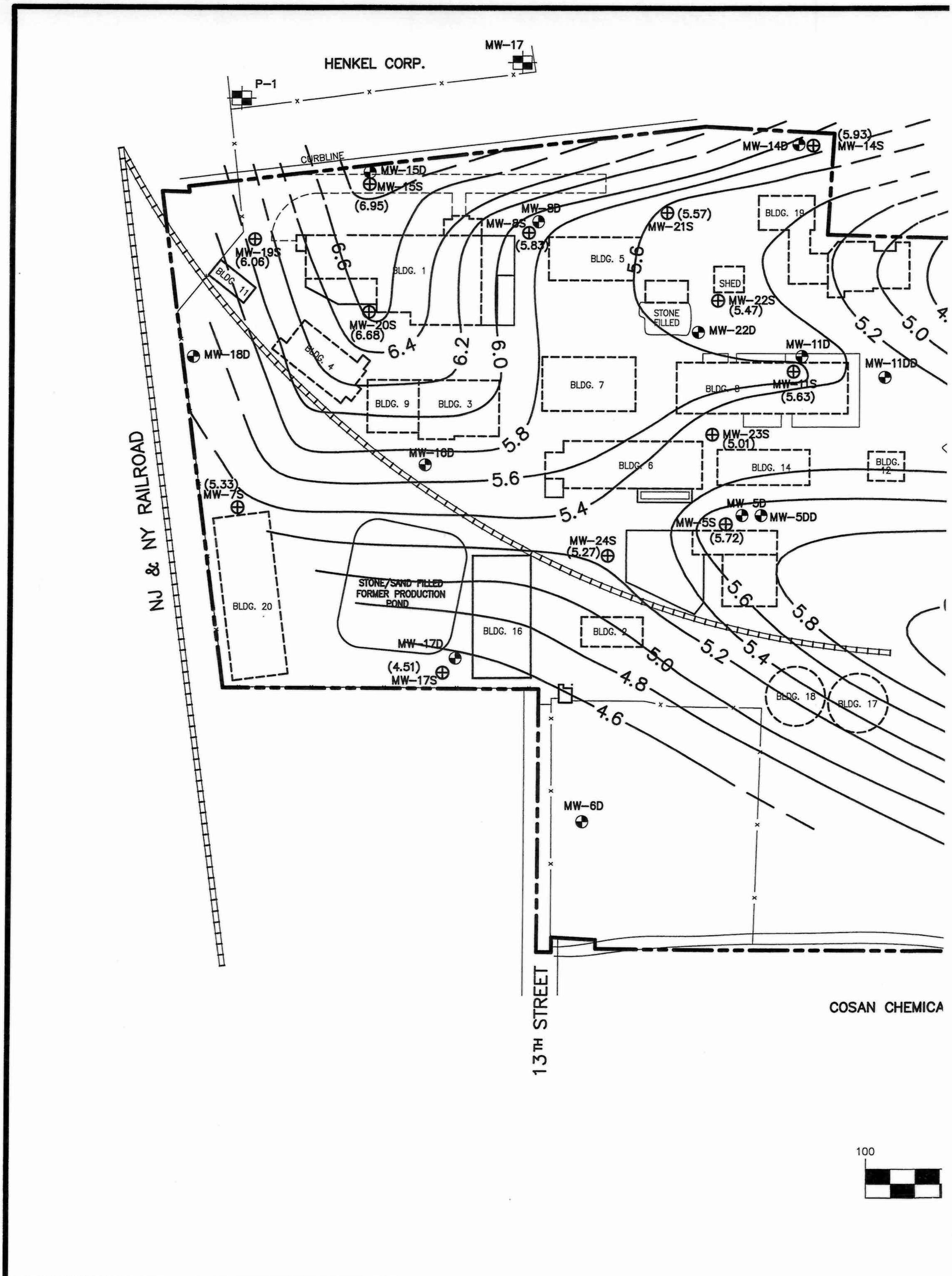
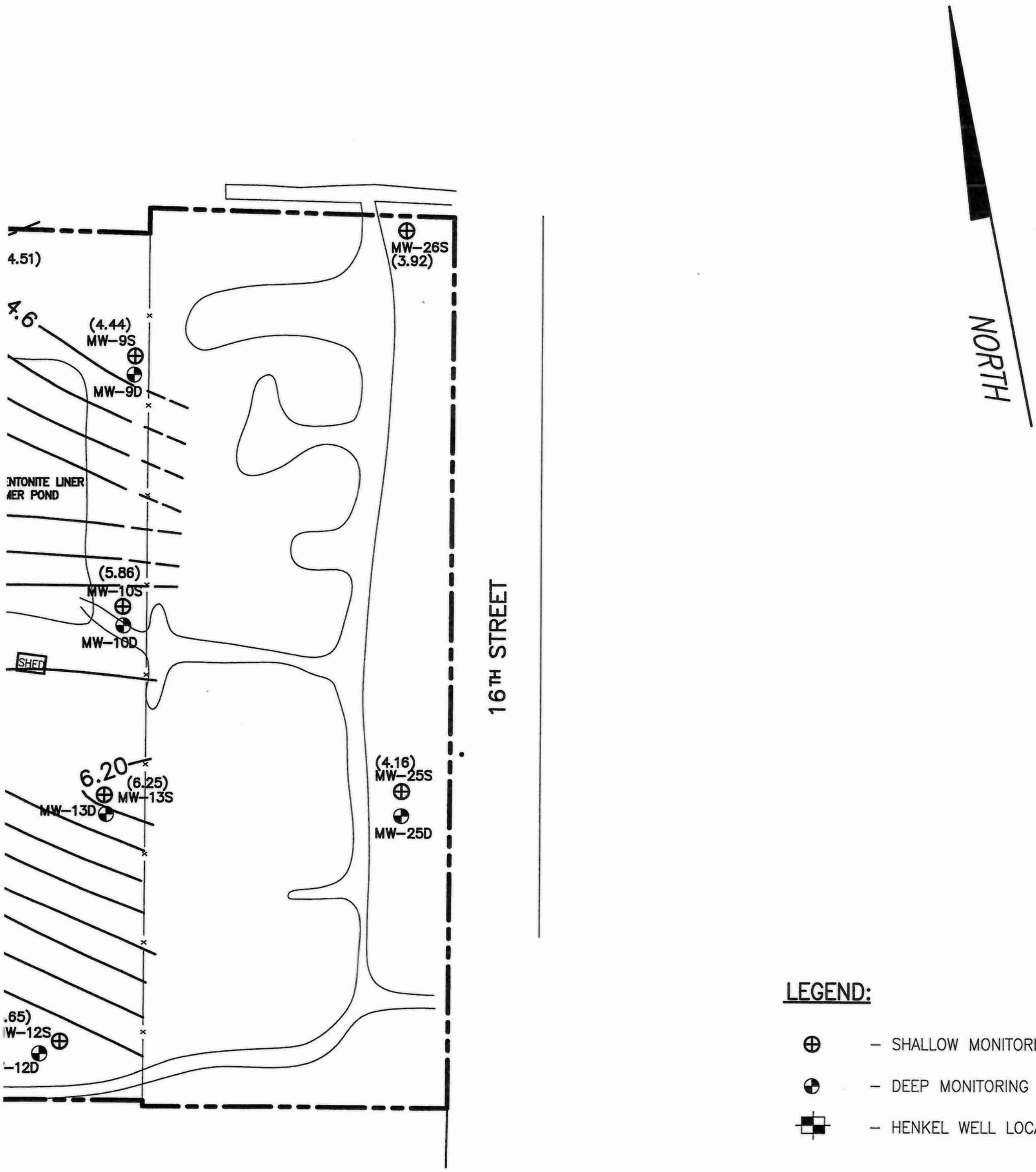


Figure C-5 Map view of the expected pattern of regional ground water flow near the Arsynco, Inc. site.



HENKEL CORP.
MW-17
P-1
CURBLINE
MW-15D
MW-15S
(6.95)
MW-14D
(5.93)
MW-14S
MW-8D
MW-8S
(5.83)
(5.57)
MW-21S
BLDG. 19
MW-19S
(6.06)
BLDG. 11
BLDG. 1
BLDG. 5
SHED
MW-22S
(5.47)
STONE FILLED
MW-22D
MW-20S
(6.68)
BLDG. 4
MW-18D
MW-11D
MW-11DD
BLDG. 7
BLDG. 8
MW-11S
(5.63)
BLDG. 9
BLDG. 3
MW-23S
(5.01)
NJ & NY RAILROAD
MW-10D
BLDG. 6
BLDG. 14
BLDG. 12
(5.33)
MW-7S
MW-5D
MW-5DD
MW-5S
(5.72)
MW-24S
(5.27)
STONE/SAND FILLED FORMER PRODUCTION POND
BLDG. 20
BLDG. 16
BLDG. 2
MW-17D
(4.51)
MW-17S
BLDG. 18
BLDG. 17
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
MW-6D
13TH STREET
COSAN CHEMICA
100



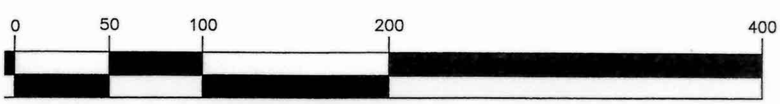
LEGEND:

⊕ – SHALLOW MONITORING WELLS

◕ – DEEP MONITORING WELLS

– HENKEL WELL LOCATIONS

GRAPHIC SCALE



(IN FEET)
1 inch = 100 ft.

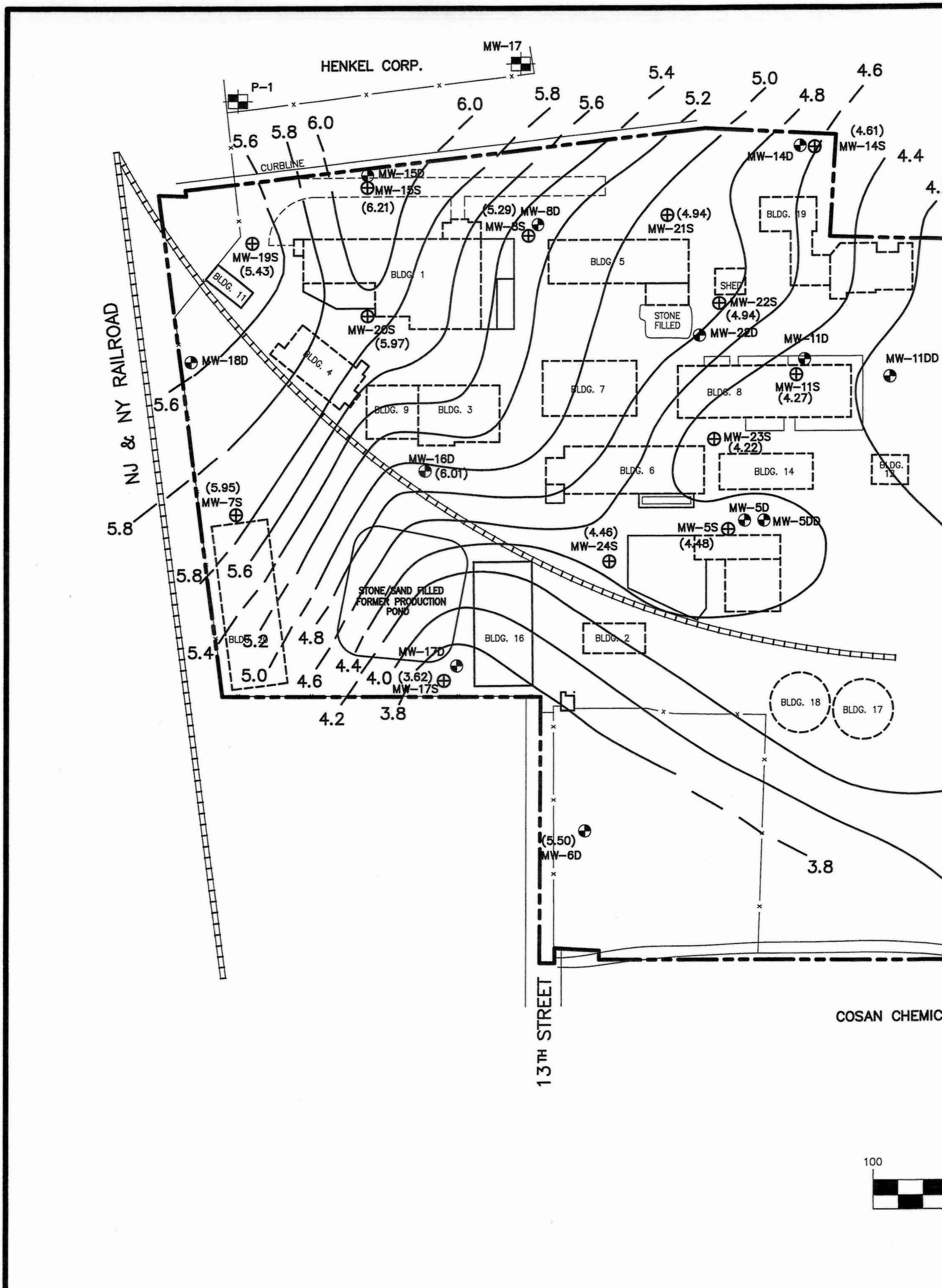
ARSYNCO, INC.

WATER TABLE MAP
FOR SHALLOW WELLS
MARCH 2002
ISRA CASE # 93024

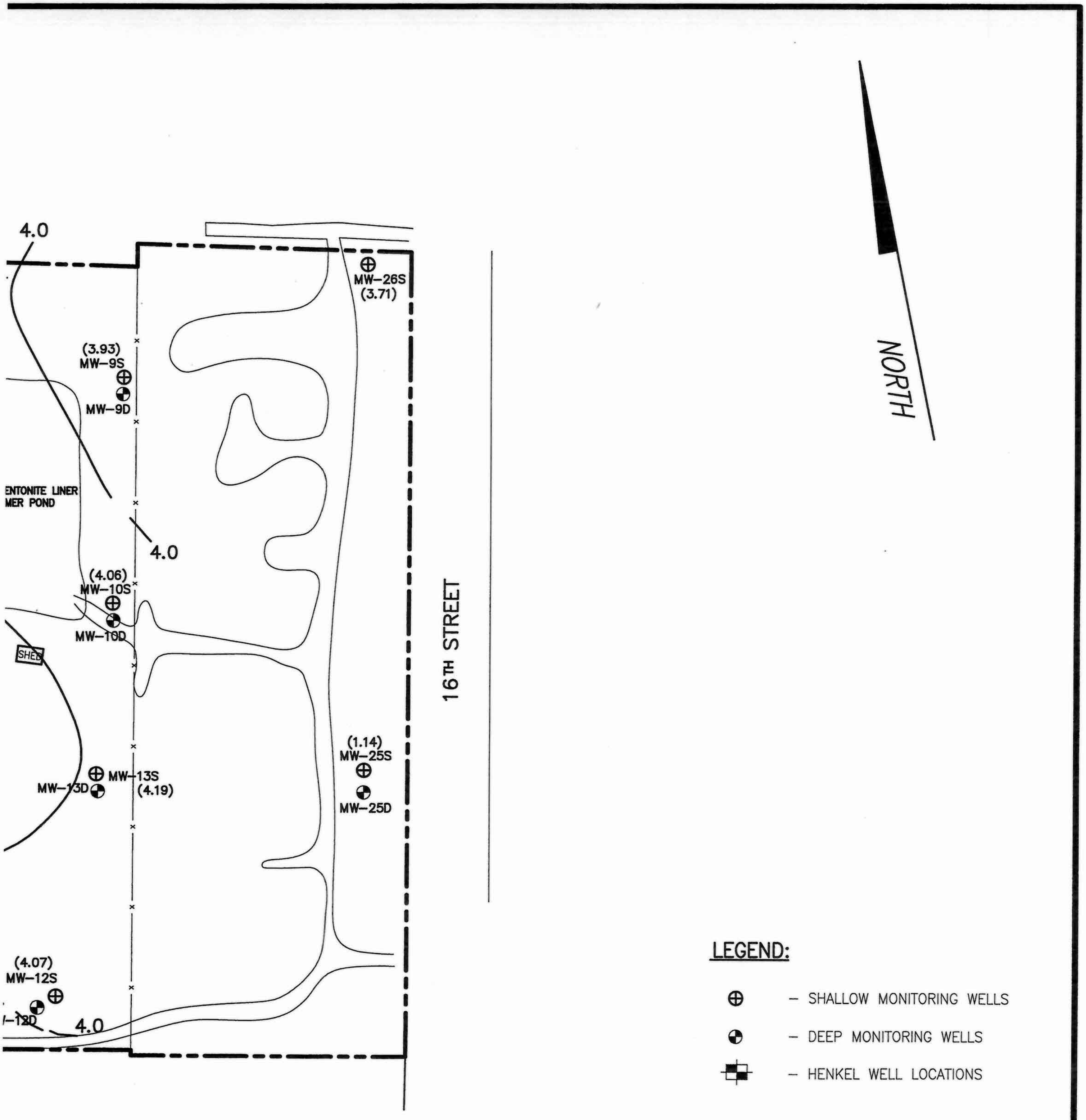
FIGURE: C–6	SCALE: 1" = 100'

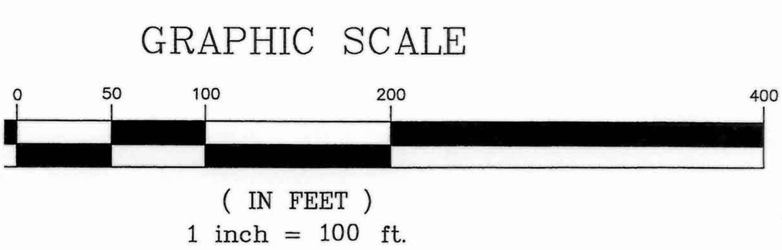
JMC ENVIRONMENTAL CONSULTANTS, INC.
1126 CONCORD DRIVE
BRICK, NEW JERSEY 08724

JMC2002–3.DWG



HENKEL CORP.
MW-17
P-1
CURBLINE
NJ & NY RAILROAD
MW-15D
MW-15S
(6.21)
(5.29) MW-8D
MW-8S
(4.94)
MW-21S
MW-19S
(5.43)
BLDG. 11
BLDG. 1
BLDG. 5
BLDG. 19
SHED
STONE FILLED
MW-22S
(4.94)
MW-22D
MW-20S
(5.97)
BLDG. 4
MW-18D
MW-14D
(4.61)
MW-14S
MW-11D
MW-11DD
BLDG. 7
BLDG. 8
MW-11S
(4.27)
BLDG. 9
BLDG. 3
MW-23S
(4.22)
MW-16D
(6.01)
BLDG. 6
BLDG. 14
BLDG. 12
(5.95)
MW-7S
MW-5D
MW-5S
MW-5DD
(4.48)
(4.46)
MW-24S
STONE/SAND FILLED FORMER PRODUCTION POND
BLDG. 16
BLDG. 2
BLDG. 20
MW-17D
(3.62)
MW-17S
BLDG. 18
BLDG. 17
(5.50)
MW-6D
13TH STREET
COSAN CHEMICA
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
100





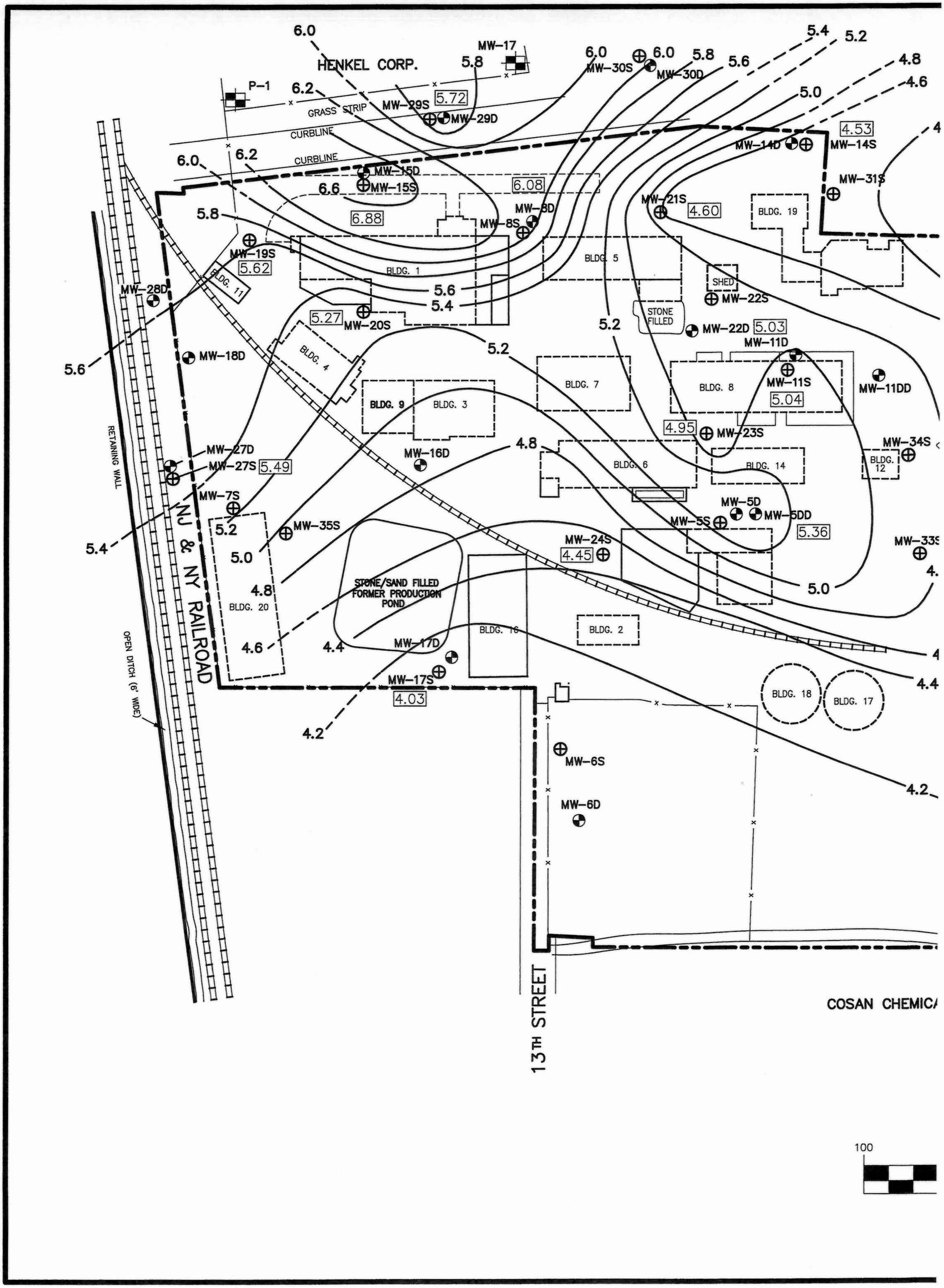
ARSYNCO, INC.

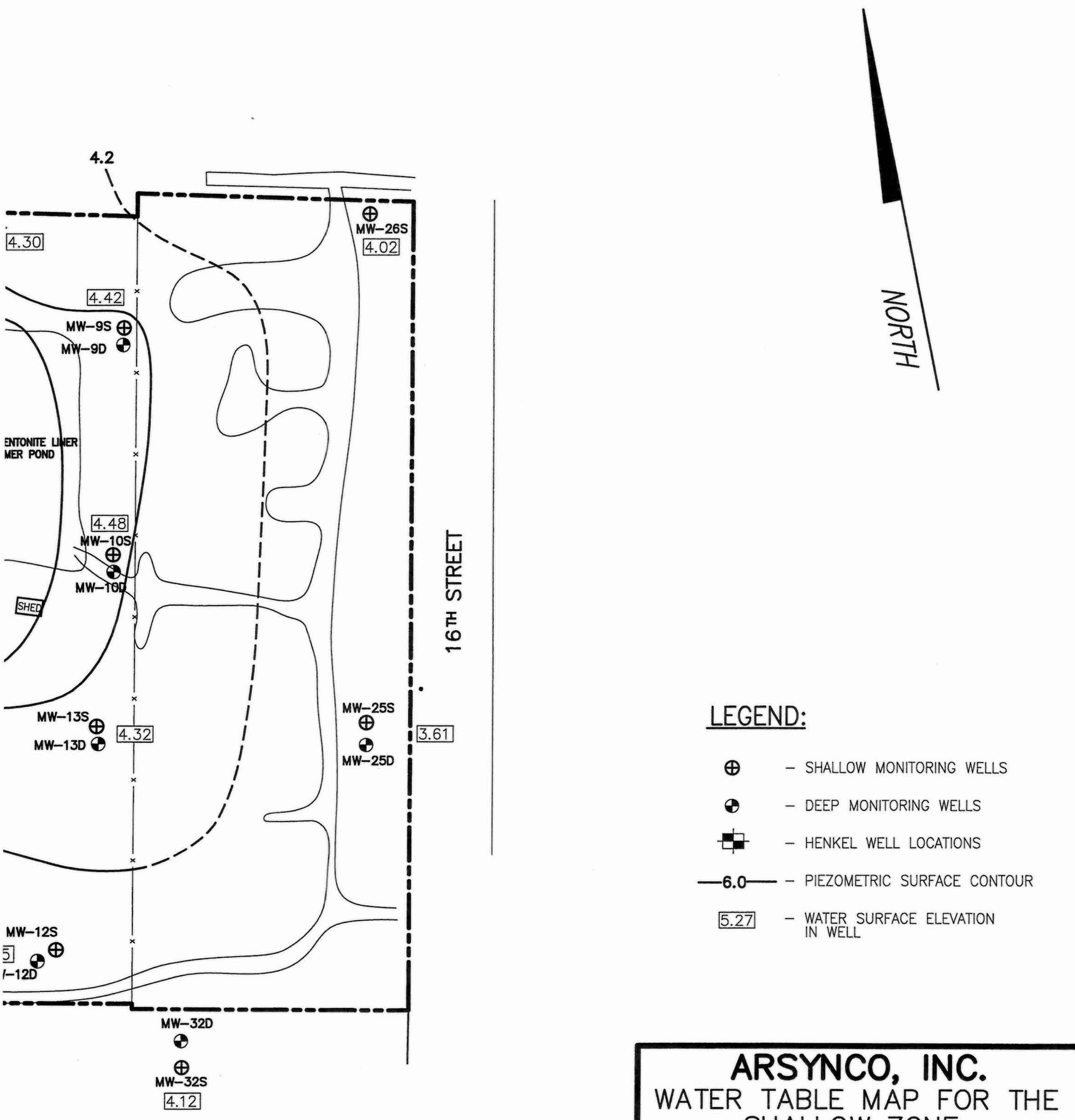
WATER TABLE SURFACE MAP
FOR THE SHALLOW ZONE
MAY 31, 2002
(12:00–12:30 PM)
ISRA CASE # 93024

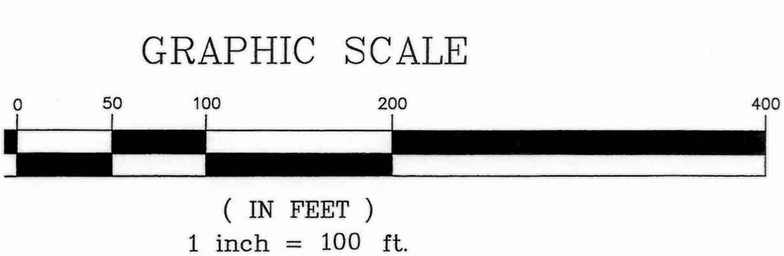
FIGURE: C–7	SCALE: 1" = 100'

JMC ENVIRONMENTAL CONSULTANTS, INC.

571 W. LAKE AVENUE, SUITE 6
BAY HEAD, NEW JERSEY 08742


HENKEL CORP.
MW-17
P-1
GRASS STRIP
CURBLINE
CURBLINE
MW-29S
5.72
MW-29D
MW-30S
MW-30D
MW-15D
MW-15S
6.08
6.88
MW-8D
MW-8S
MW-21S
4.60
BLDG. 19
MW-14D
MW-14S
4.53
MW-31S
MW-19S
5.62
BLDG. 11
BLDG. 1
BLDG. 5
SHED
MW-22S
STONE FILLED
MW-22D
5.03
MW-28D
5.27
MW-20S
MW-18D
BLDG. 4
BLDG. 9
BLDG. 3
BLDG. 7
BLDG. 8
MW-11D
MW-11S
5.04
MW-11DD
4.95
MW-23S
RETAINING WALL
MW-27D
MW-27S
5.49
MW-16D
BLDG. 6
BLDG. 14
MW-34S
BLDG. 12
MW-7S
NJ & NY RAILROAD
MW-5D
MW-5DD
MW-5S
5.36
MW-35S
MW-24S
4.45
MW-33S
STONE/SAND FILLED FORMER PRODUCTION POND
BLDG. 20
BLDG. 16
BLDG. 2
OPEN DITCH (6' WIDE)
MW-17D
MW-17S
4.03
BLDG. 18
BLDG. 17
MW-6S
MW-6D
13TH STREET
COSAN CHEMIC
100
6.0
6.2
6.6
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2





ARSYNCO, INC.

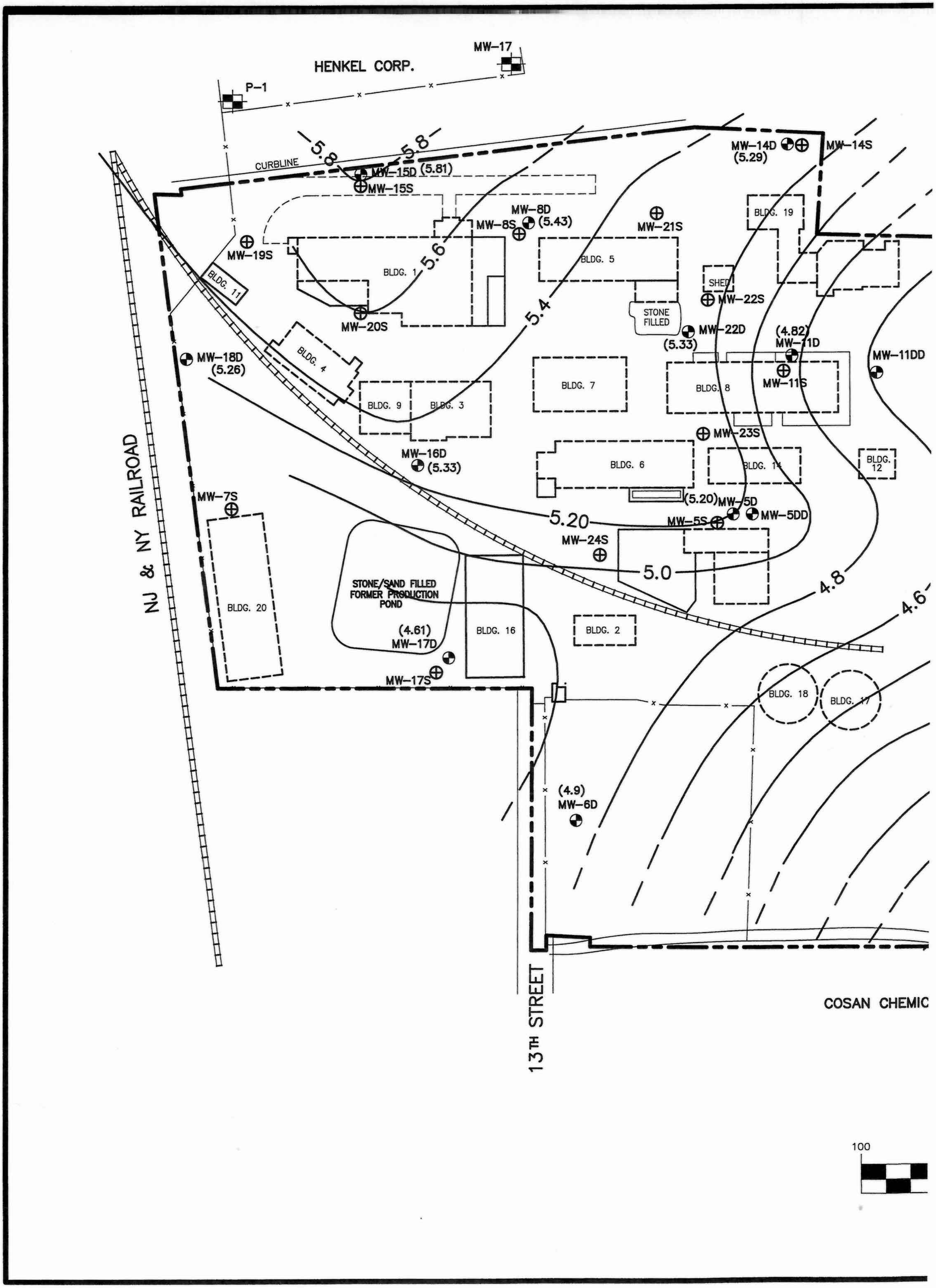
WATER TABLE MAP FOR THE SHALLOW ZONE
MAY 19, 2003
WATER LEVELS COLLECTED BETWEEN 8:14 & 9:26 AM
ISRA CASE # 93024

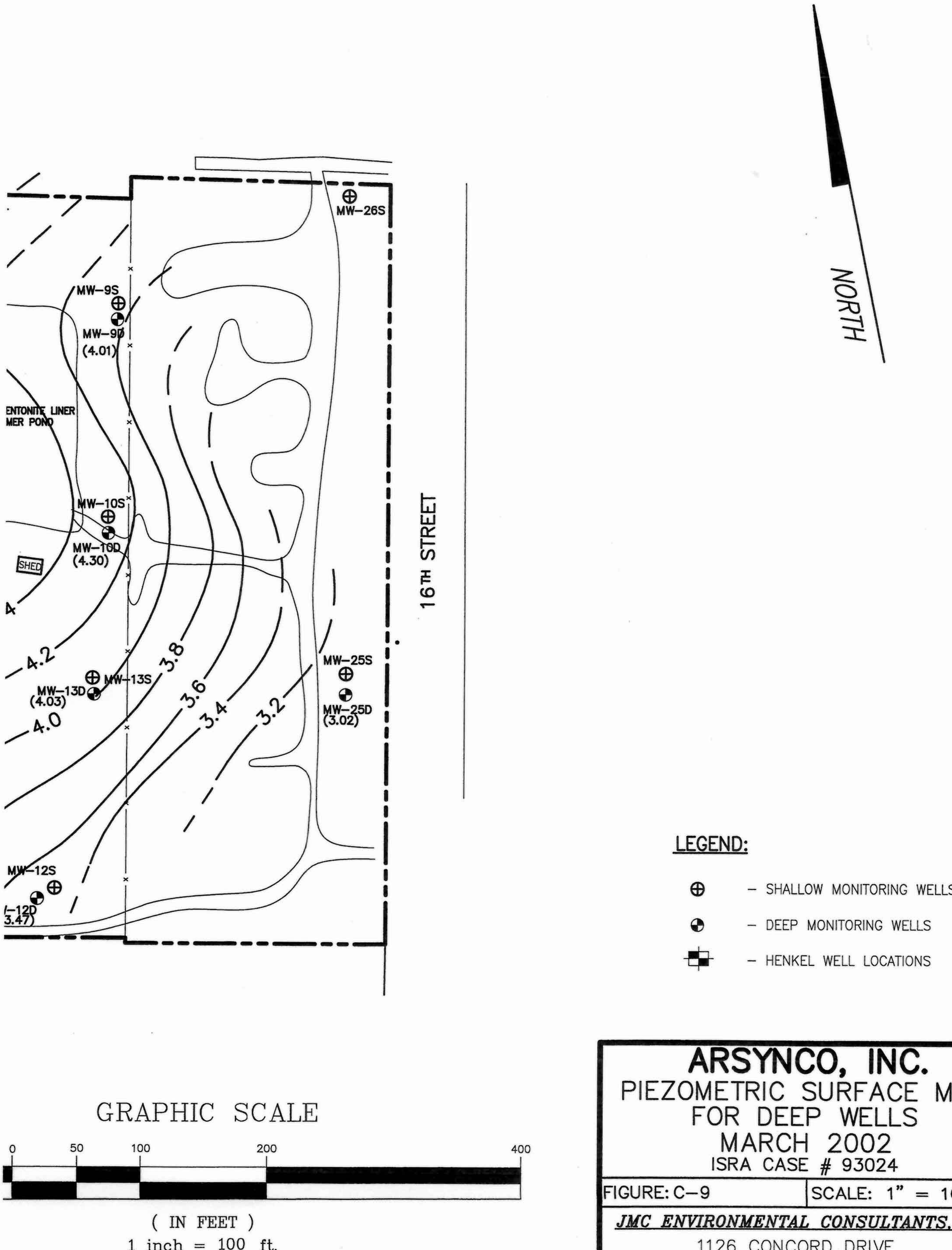
FIGURE: C-8	SCALE: 1" = 100'

JMC ENVIRONMENTAL CONSULTANTS, INC.

571 W. LAKE AVENUE, SUITE 6
BAY HEAD, NEW JERSEY 08742

JMC2003-6.DWG


HENKEL CORP.
MW-17
P-1
CURBLINE
5.8
MW-15D (5.81)
MW-15S
MW-8D
MW-8S (5.43)
MW-21S
MW-14D
(5.29)
MW-14S
BLDG. 19
MW-19S
BLDG. 11
BLDG. 1
5.6
BLDG. 5
SHED
MW-22S
MW-20S
STONE FILLED
5.4
MW-22D
(5.33)
(4.82)
MW-11D
MW-11DD
MW-18D
(5.26)
BLDG. 4
BLDG. 7
BLDG. 8
MW-11S
BLDG. 9
BLDG. 3
MW-23S
NJ & NY RAILROAD
MW-16D
(5.33)
BLDG. 6
BLDG. 14
BLDG. 12
MW-7S
(5.20)MW-5D
MW-5DD
5.20
MW-5S
MW-24S
5.0
4.8
4.6
STONE/SAND FILLED FORMER PRODUCTION POND
BLDG. 20
BLDG. 16
BLDG. 2
(4.61)
MW-17D
MW-17S
BLDG. 18
BLDG. 17
(4.9)
MW-6D
13TH STREET
COSAN CHEMIC
100



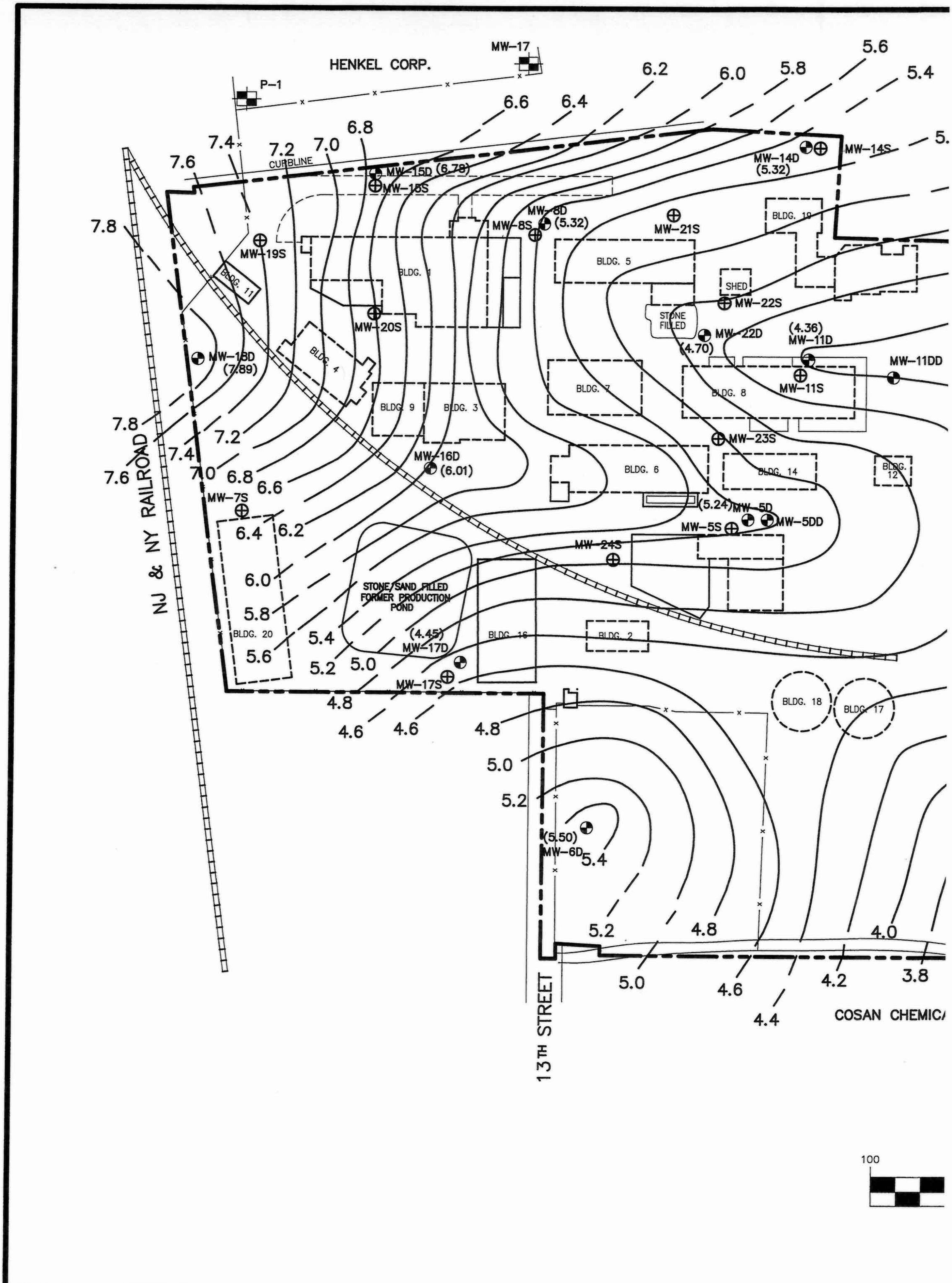
ARSYNCO, INC.

PIEZOMETRIC SURFACE MAP
FOR DEEP WELLS
MARCH 2002
ISRA CASE # 93024

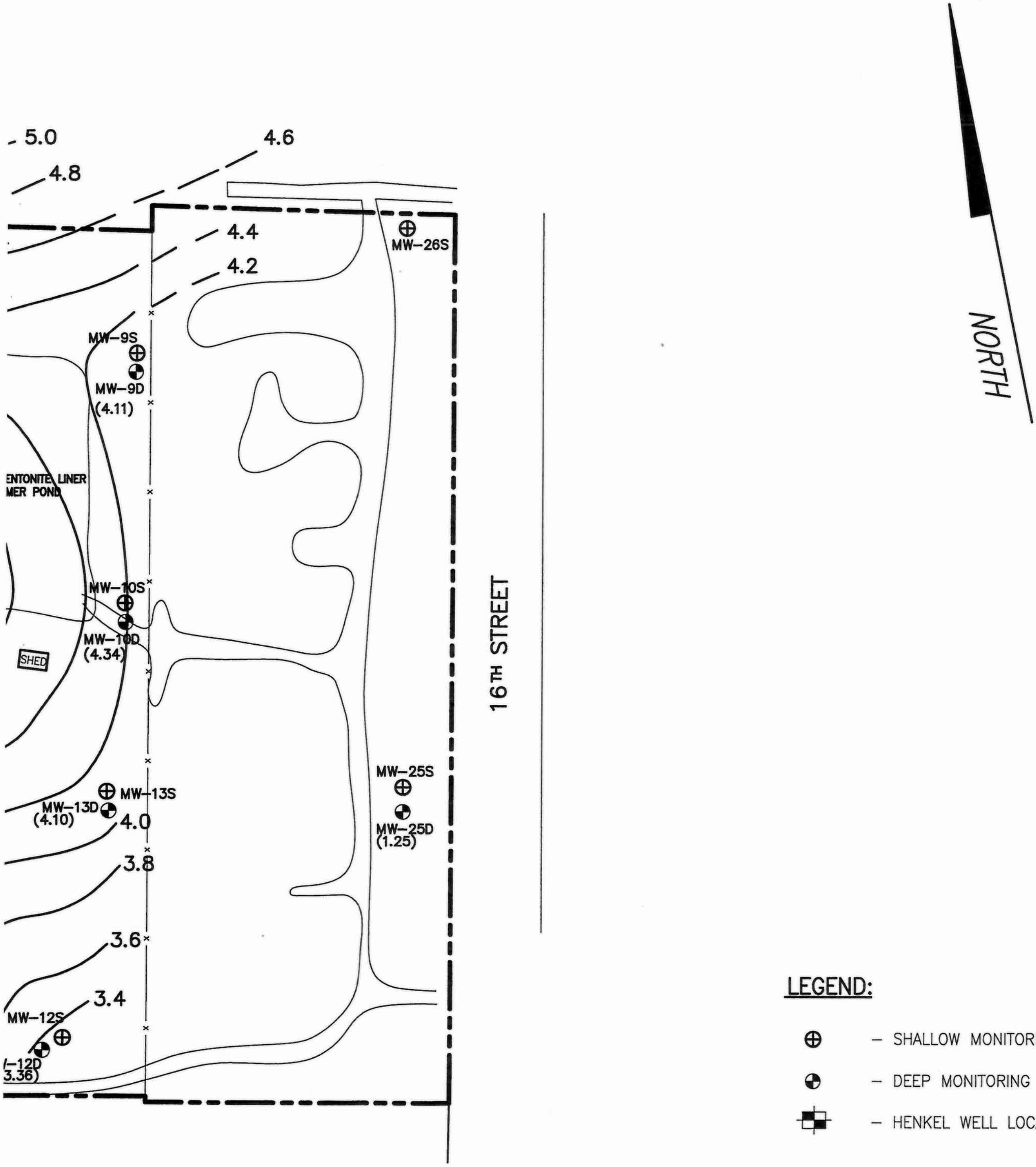
FIGURE: C-9	SCALE: 1" = 100'

JMC ENVIRONMENTAL CONSULTANTS, INC.
1126 CONCORD DRIVE
BRICK, NEW JERSEY 08724

JMC2002-3.DWG



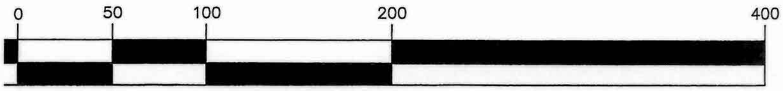
HENKEL CORP.
P-1
MW-17
CURBLINE
NJ & NY RAILROAD
13TH STREET
COSAN CHEMIC
MW-15D (6.78)
MW-15S
MW-8D (5.32)
MW-8S
MW-21S
MW-14D (5.32)
MW-14S
MW-19S
MW-20S
MW-22S
MW-22D (4.70)
(4.36) MW-11D
MW-11DD
MW-11S
MW-18D (7.89)
MW-23S
MW-16D (6.01)
(5.24) MW-5D
MW-5S
MW-5DD
MW-7S
MW-24S
(4.45) MW-17D
MW-17S
(5.50) MW-6D
BLDG. 1
BLDG. 2
BLDG. 3
BLDG. 4
BLDG. 5
BLDG. 6
BLDG. 7
BLDG. 8
BLDG. 9
BLDG. 11
BLDG. 12
BLDG. 14
BLDG. 16
BLDG. 17
BLDG. 18
BLDG. 19
BLDG. 20
SHED
STONE FILLED
STONE/SAND FILLED FORMER PRODUCTION POND
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
100



LEGEND:

- SHALLOW MONITORING WELLS
- DEEP MONITORING WELLS
- HENKEL WELL LOCATIONS

GRAPHIC SCALE



(IN FEET)
1 inch = 100 ft.

JMC2003-7

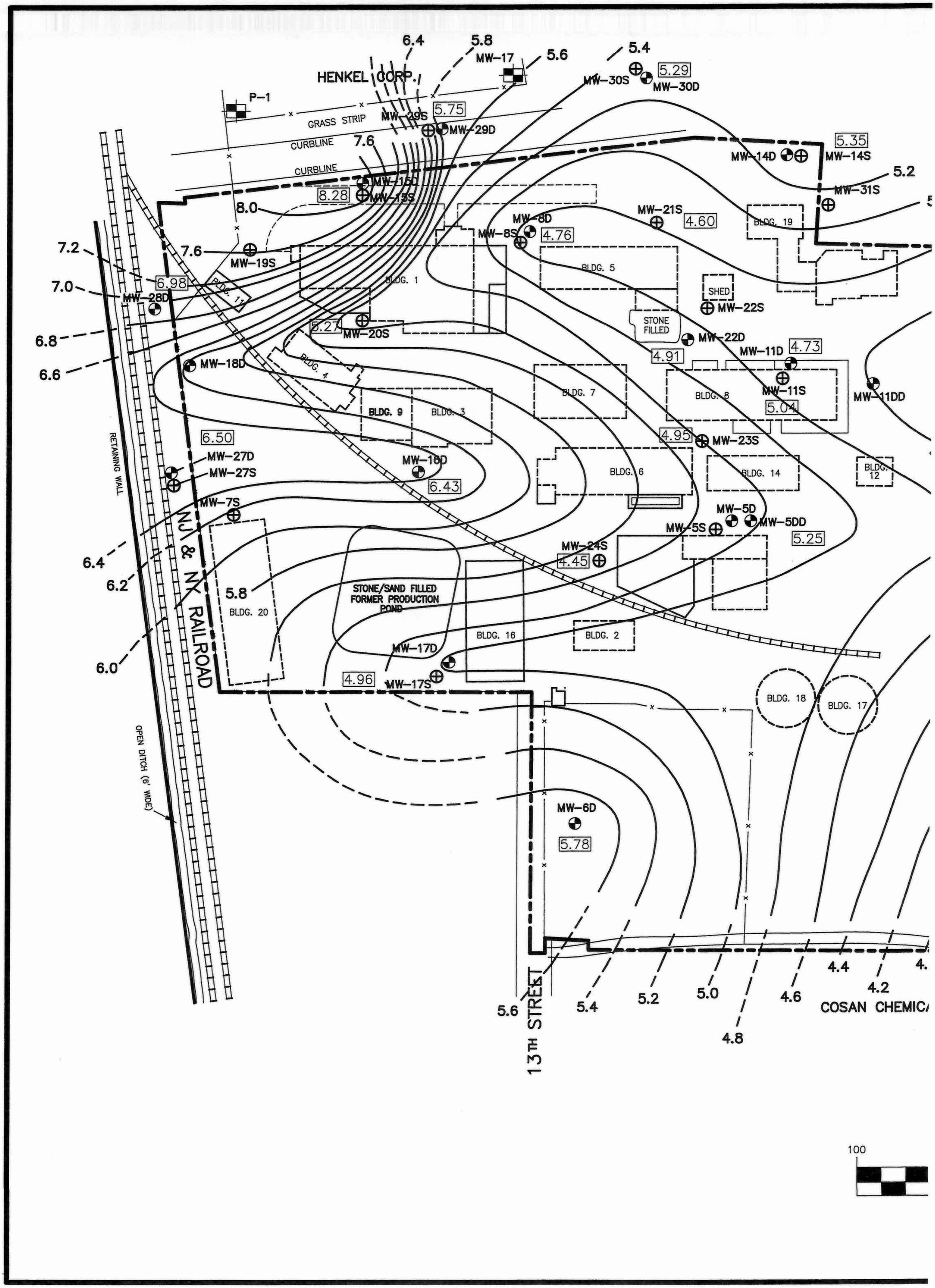
ARSYNCO, INC.

PIEZOMETRIC SURFACE MAP
FOR THE DEEP ZONE
MAY 31, 2002
(12:00–12:30 PM)
ISRA CASE # 93024

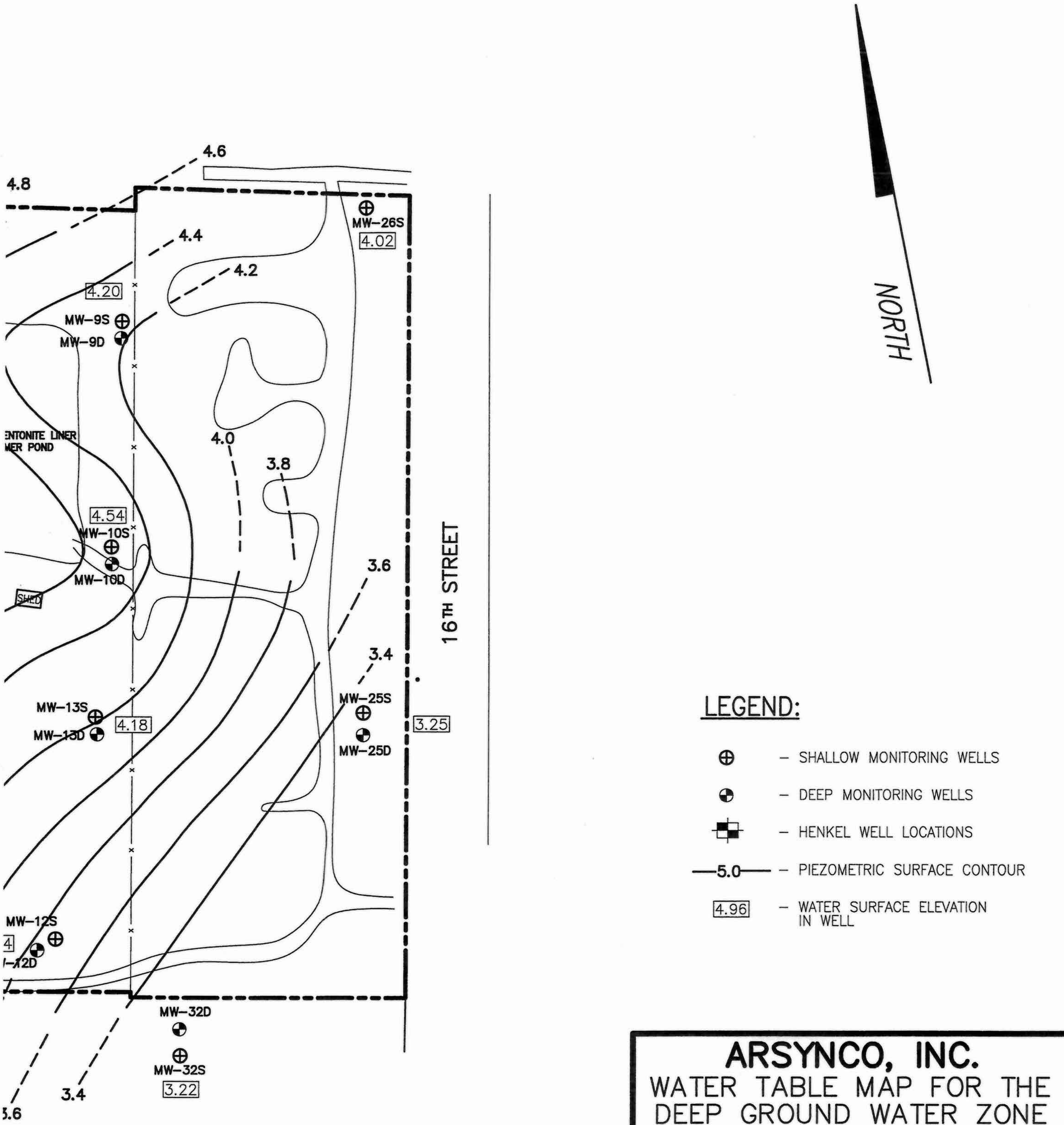
FIGURE: C–10	SCALE: 1" = 100'

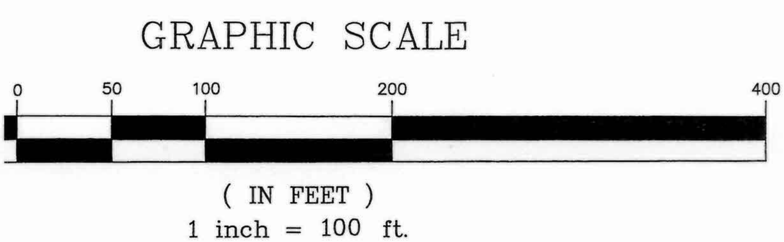
JMC ENVIRONMENTAL CONSULTANTS, INC.

571 W. LAKE AVENUE, SUITE 6
BAY HEAD, NEW JERSEY 08742



HENKEL CORP.
P-1
MW-17
GRASS STRIP
CURBLINE
CURBLINE
MW-29S
5.75
MW-29D
MW-30S
5.29
MW-30D
5.35
MW-14D
MW-14S
MW-31S
MW-15D
8.28
MW-15S
MW-19S
MW-8D
MW-8S
4.76
MW-21S
4.60
BLDG. 19
BLDG. 1
BLDG. 5
SHED
MW-22S
STONE FILLED
MW-22D
6.98
BLDG. 11
MW-28D
5.27
MW-20S
BLDG. 4
MW-18D
4.91
MW-11D
4.73
BLDG. 7
BLDG. 8
MW-11S
5.04
MW-11DD
BLDG. 9
BLDG. 3
RETAINING WALL
6.50
MW-27D
MW-27S
MW-16D
6.43
4.95
MW-23S
BLDG. 6
BLDG. 14
BLDG. 12
MW-7S
MW-5D
MW-5S
MW-5DD
5.25
MW-24S
4.45
NJ & NY RAILROAD
STONE/SAND FILLED FORMER PRODUCTION POND
BLDG. 20
BLDG. 16
BLDG. 2
MW-17D
4.96
MW-17S
BLDG. 18
BLDG. 17
OPEN DITCH (6' WIDE)
MW-6D
5.78
13TH STREET
COSAN CHEMIC
8.0
7.6
7.6
7.2
7.0
6.8
6.6
6.4
6.4
6.2
6.0
5.8
5.8
5.6
5.6
5.4
5.4
5.2
5.2
5.0
4.8
4.6
4.4
4.2
100





ARSYNCO, INC.

WATER TABLE MAP FOR THE DEEP GROUND WATER ZONE
MAY 19, 2003
WATER LEVELS COLLECTED BETWEEN 8:14 & 9:26 AM

ISRA CASE # 93024

FIGURE: C–11	SCALE: 1" = 100'

JMC ENVIRONMENTAL CONSULTANTS, INC.

571 W. LAKE AVENUE, SUITE 6
BAY HEAD, NEW JERSEY 08742

JMC2003–6.DWG

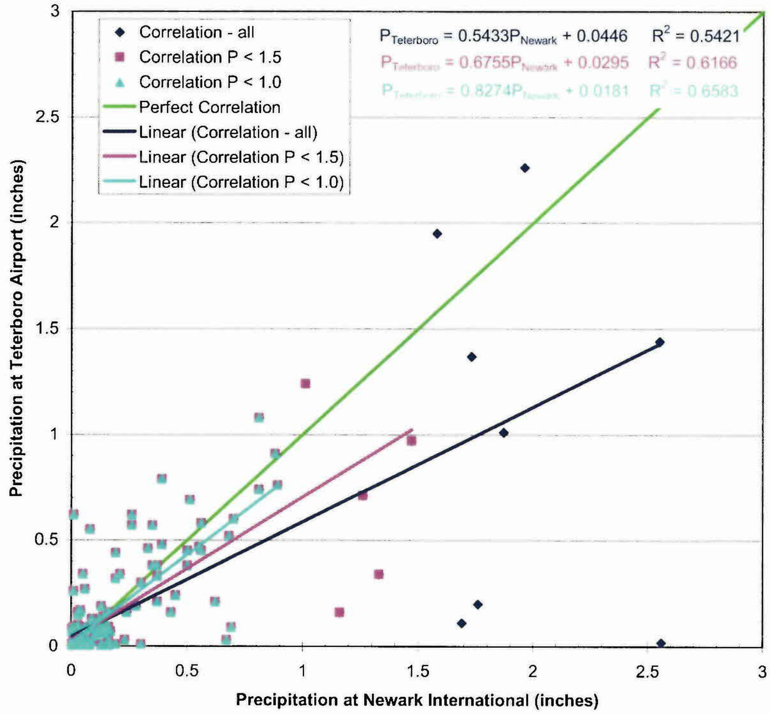


Figure C-12. Correlation between daily precipitation recorded at Teterboro Airport and Newark International Airport for January through August 2003. Three correlations are presented: one with all data included, a second with precipitation values greater than 1.5 inches at either site removed from the data set, and a third with precipitation values greater than 1.0 inch at either site removed from the data set .

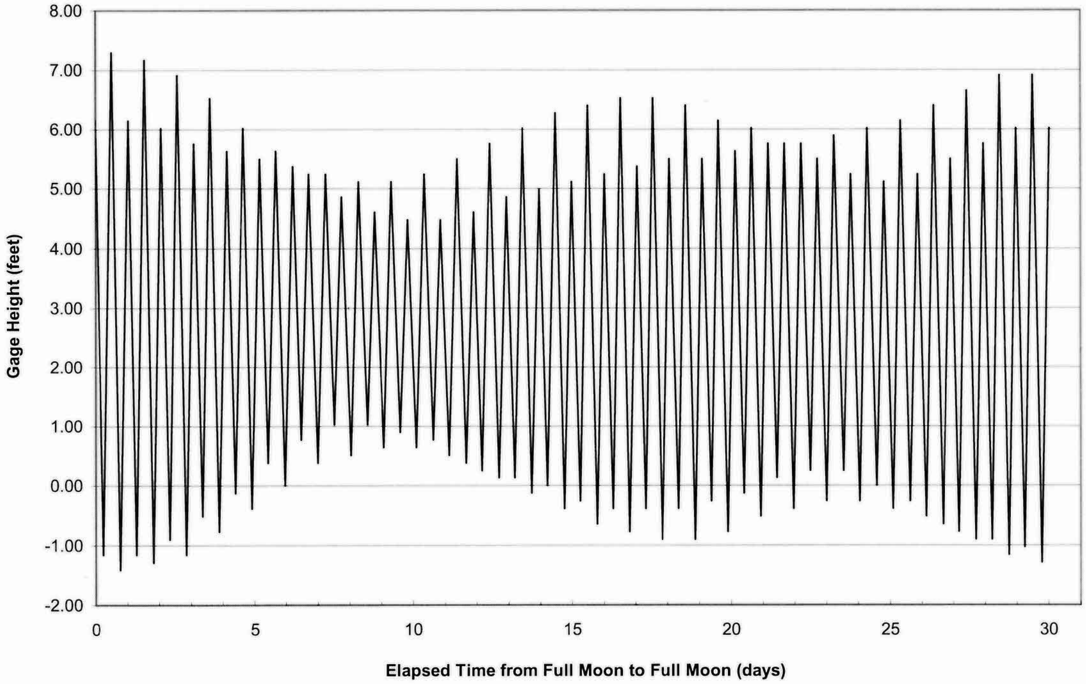


Figure C-13. Tide predictions for the Hackensack River at the Hackensack, NJ gauging station for January 1999. The data cover a complete lunar cycle from one full moon to the next. (Data source: International Marine 2002)

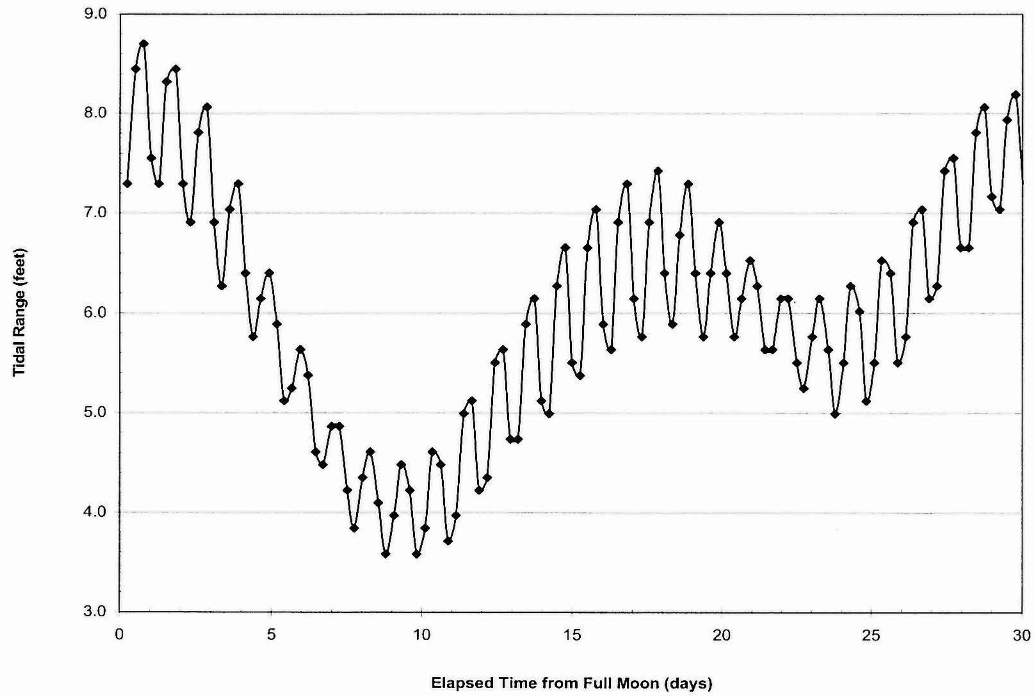


Figure C-14. Magnitude of the tidal range (difference between successive high and low stages) for the Hackensack River at Hackensack, NJ for January 1999. The data cover a complete lunar cycle from one full moon to the next. (Data source: International Marine 2002).

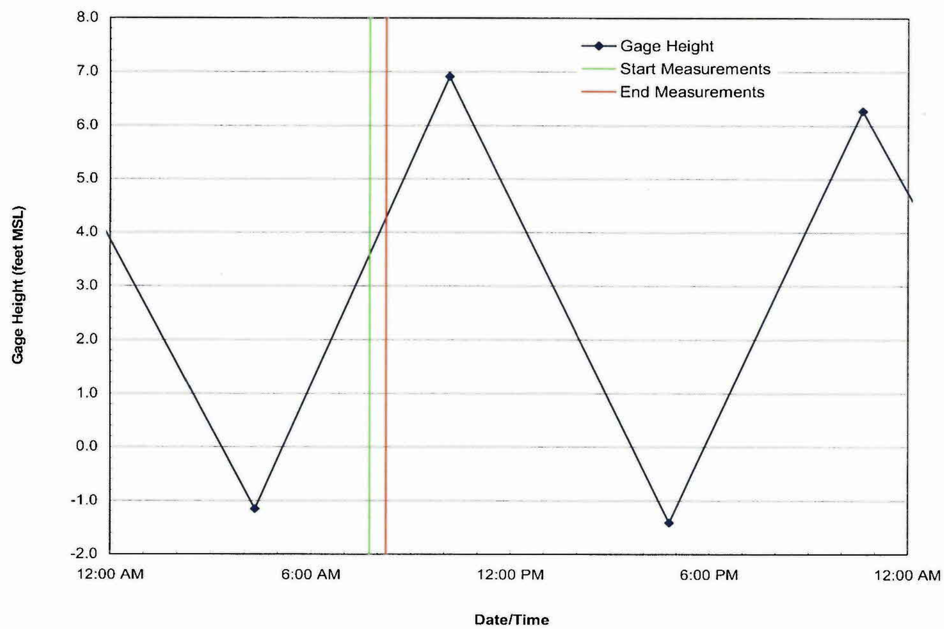


Figure C-15. Tide predictions for the Hackensack River at Hackensack, NJ February 2, 1995. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

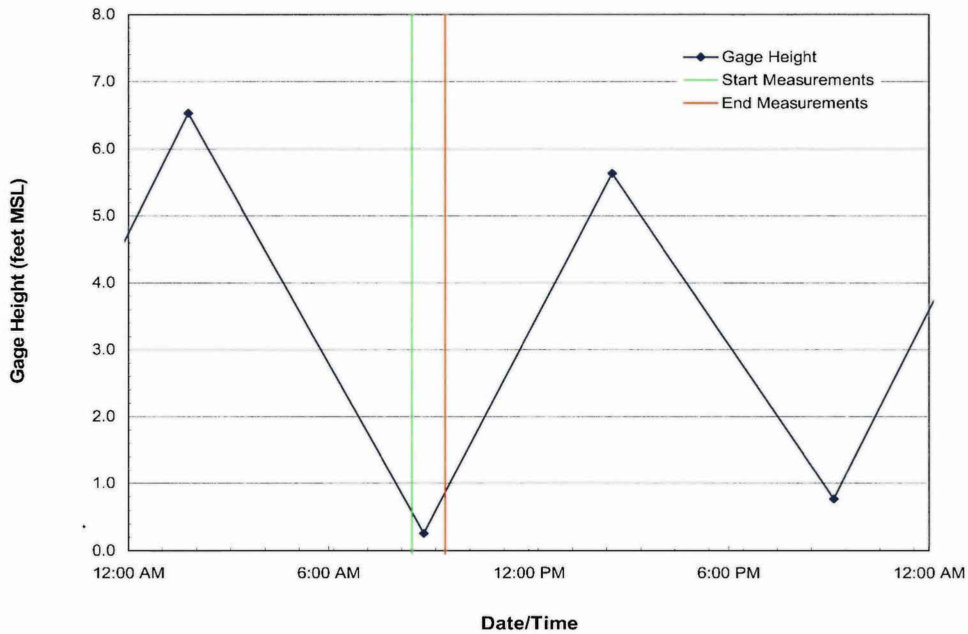


Figure C-16. Tide predictions for the Hackensack River at Hackensack, NJ April 10, 1996. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

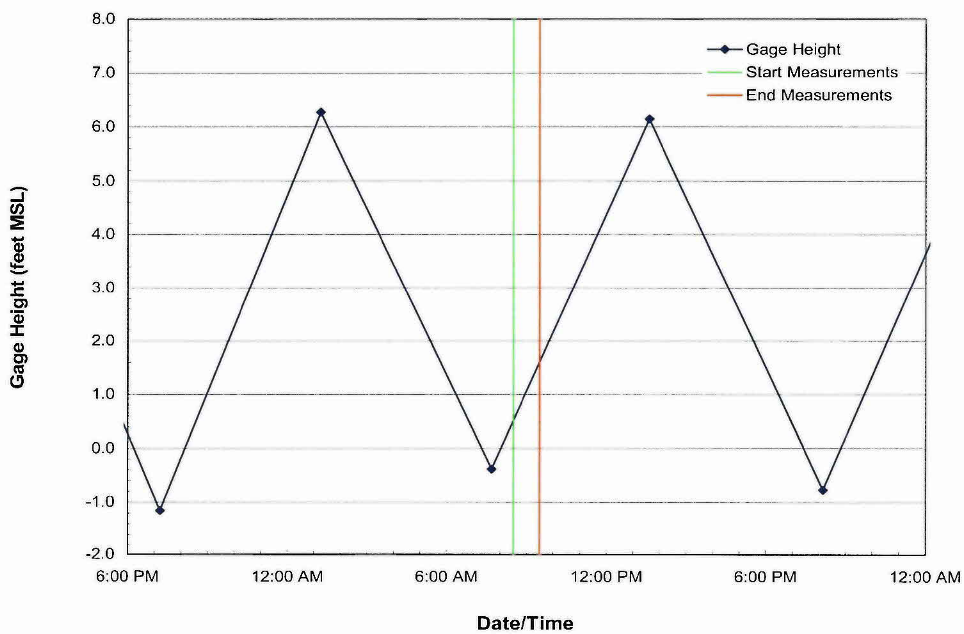


Figure C-17. Tide predictions for the Hackensack River at Hackensack, NJ January 13-14, 1997. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

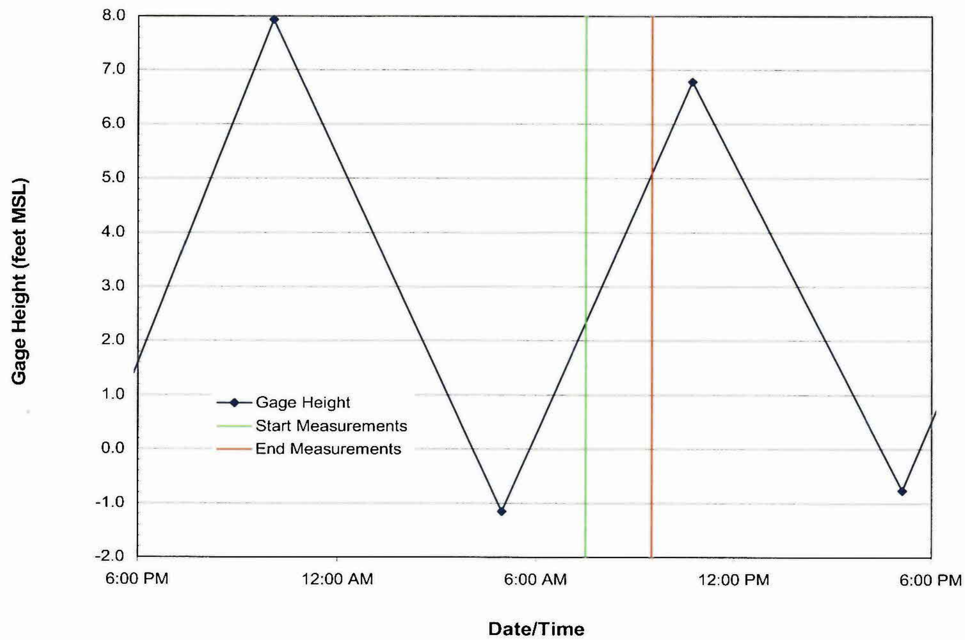


Figure C-18. Tide predictions for the Hackensack River at Hackensack, NJ April 27-28, 1998. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

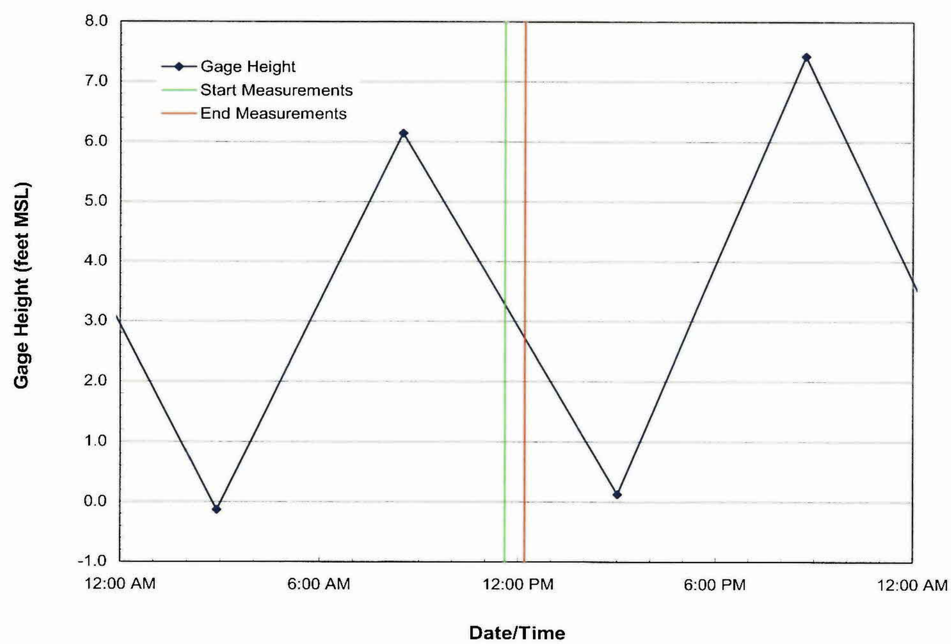


Figure C-19. Tide predictions for the Hackensack River at Hackensack, NJ August 6-7, 1998. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

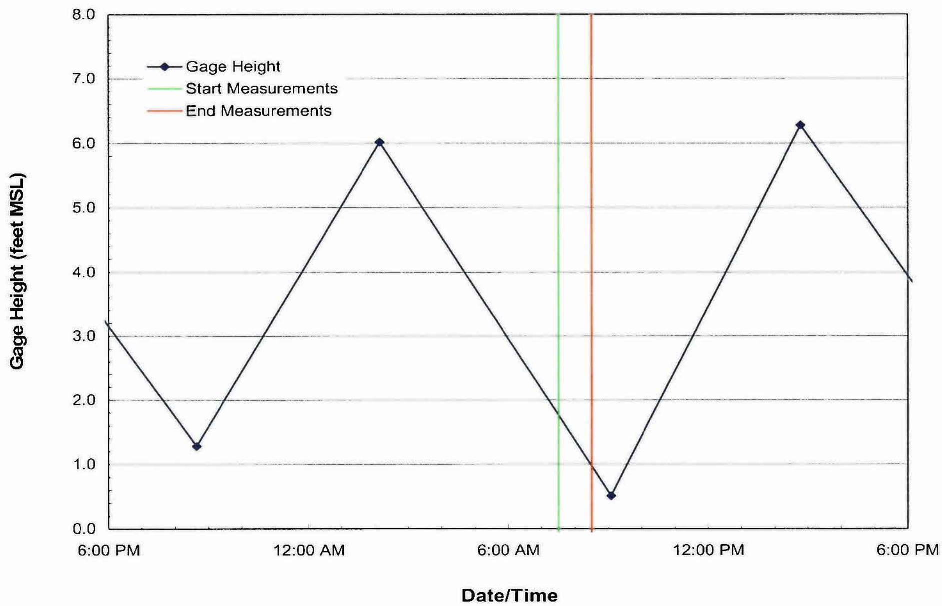


Figure C-20. Tide predictions for the Hackensack River at Hackensack, NJ July 5-6, 1999. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

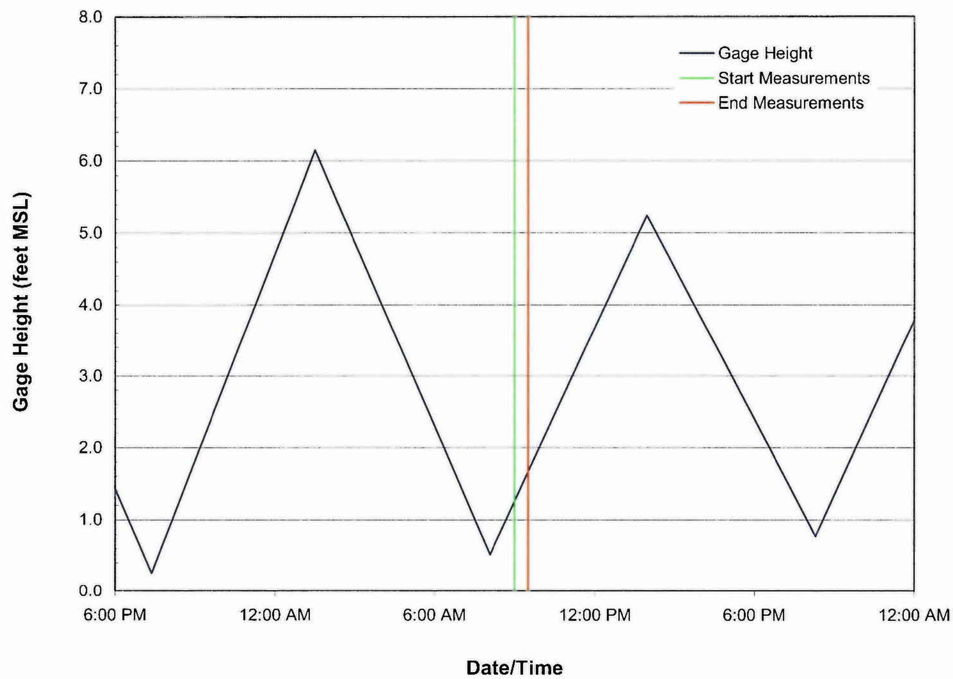


Figure C-21. Tide predictions for the Hackensack River at Hackensack, NJ March 14-15, 2001. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

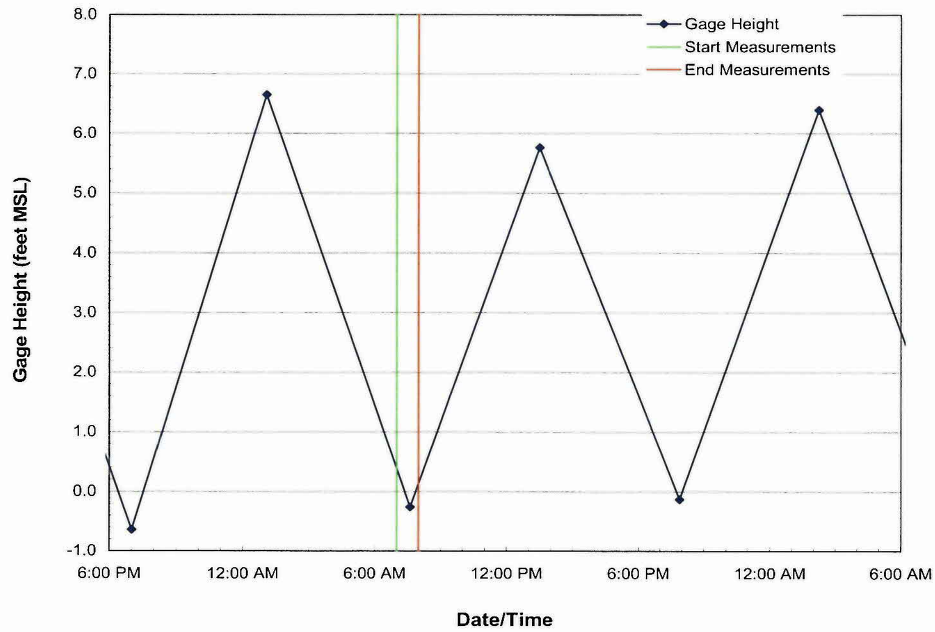


Figure C-22. Tide predictions for the Hackensack River at Hackensack, NJ March 3-4, 2002. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

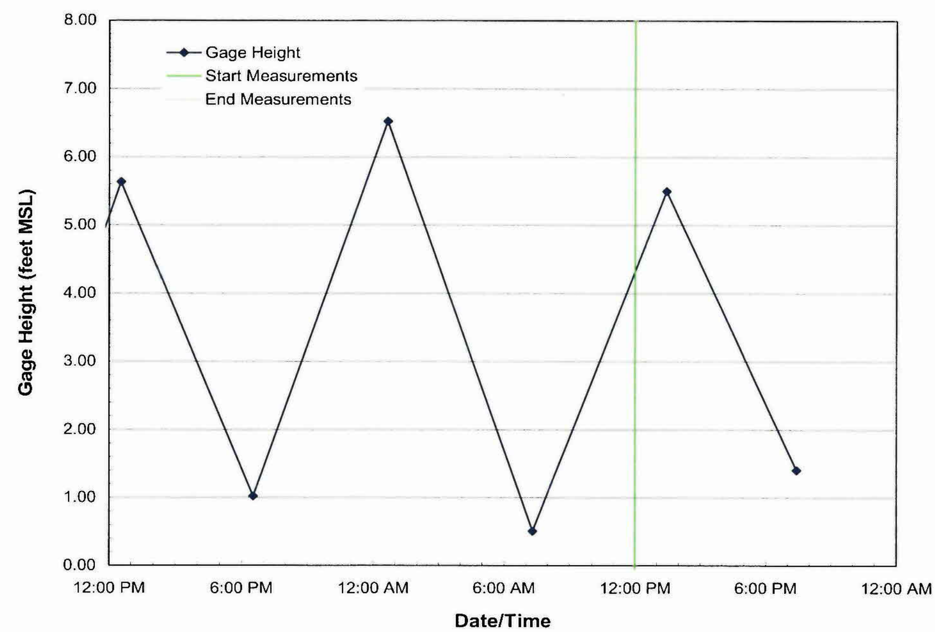


Figure C-23. Tide predictions for the Hackensack River at Hackensack, NJ May 30-31, 2002. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

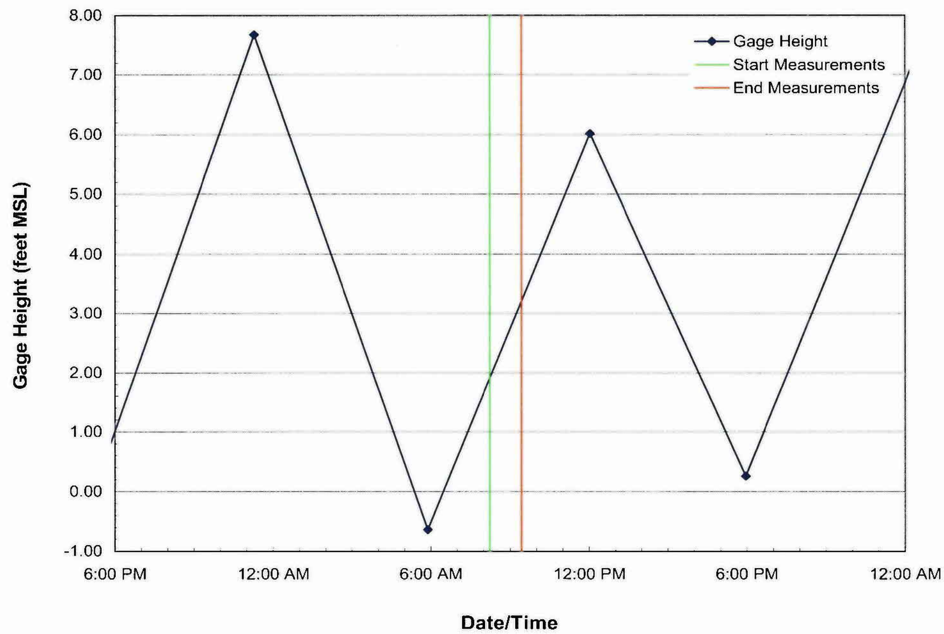


Figure C-24. Tide predictions for the Hackensack River at Hackensack, NJ May 18-19, 2003. Vertical lines bracket the interval during which water level measurements were collected for generating flow maps.

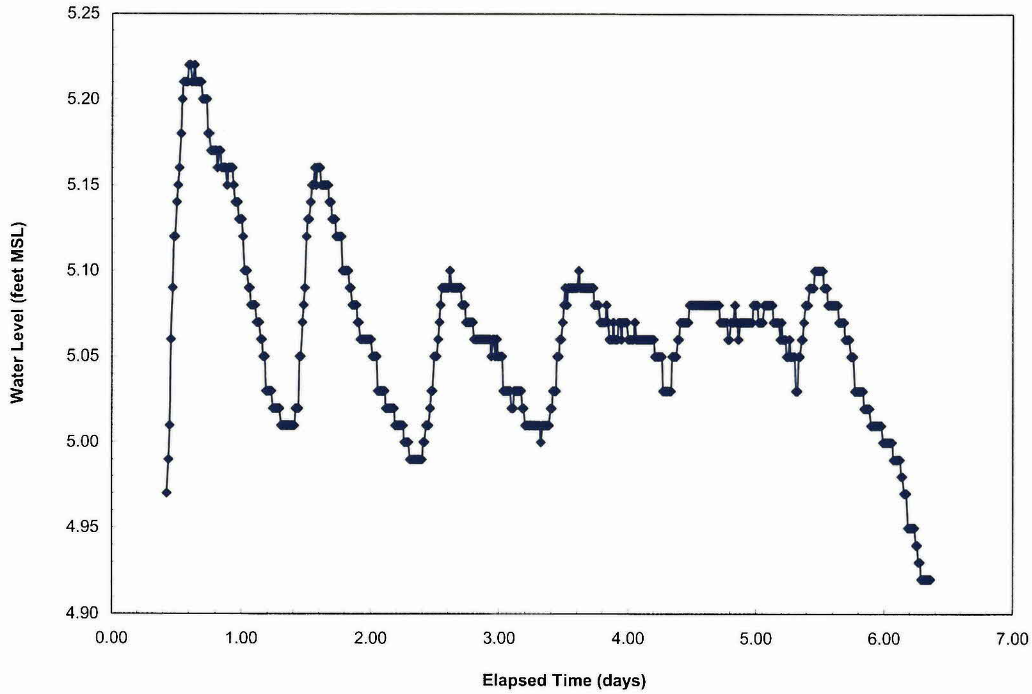


Figure C-25. Water levels illustrating tidal cycles in well MW-8S, February 16-22. 1995.

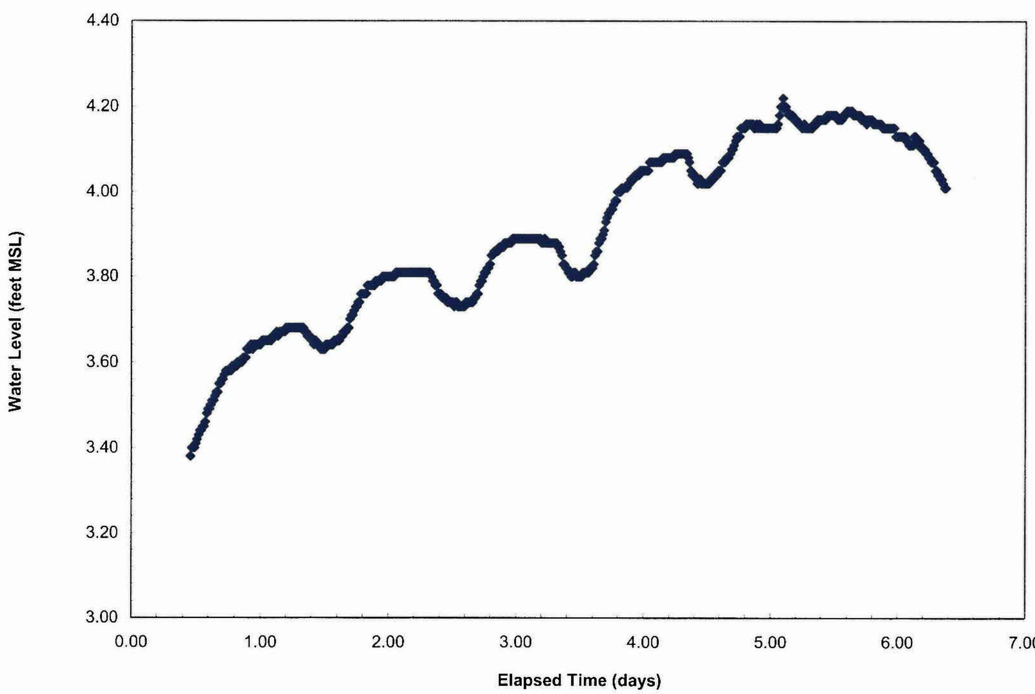


Figure C-26. Water levels illustrating recharge and tidal cycles in well MW-10S, February 16-22. 1995.

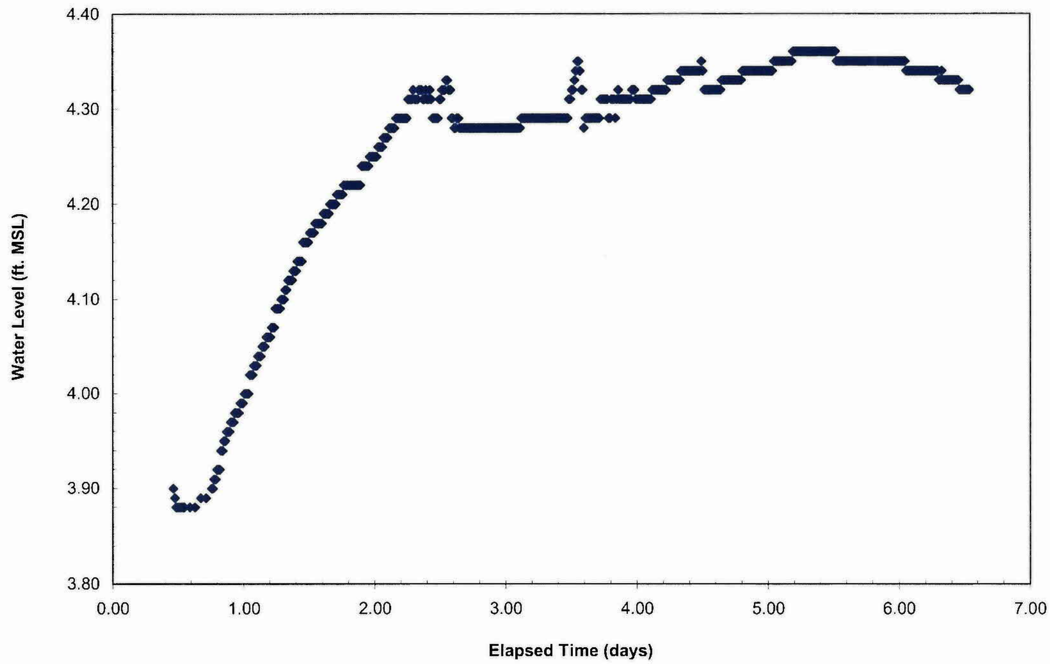


Figure C-27. Water levels illustrating recharge and tidal cycles in well MW-12S, February 16-22. 1995.

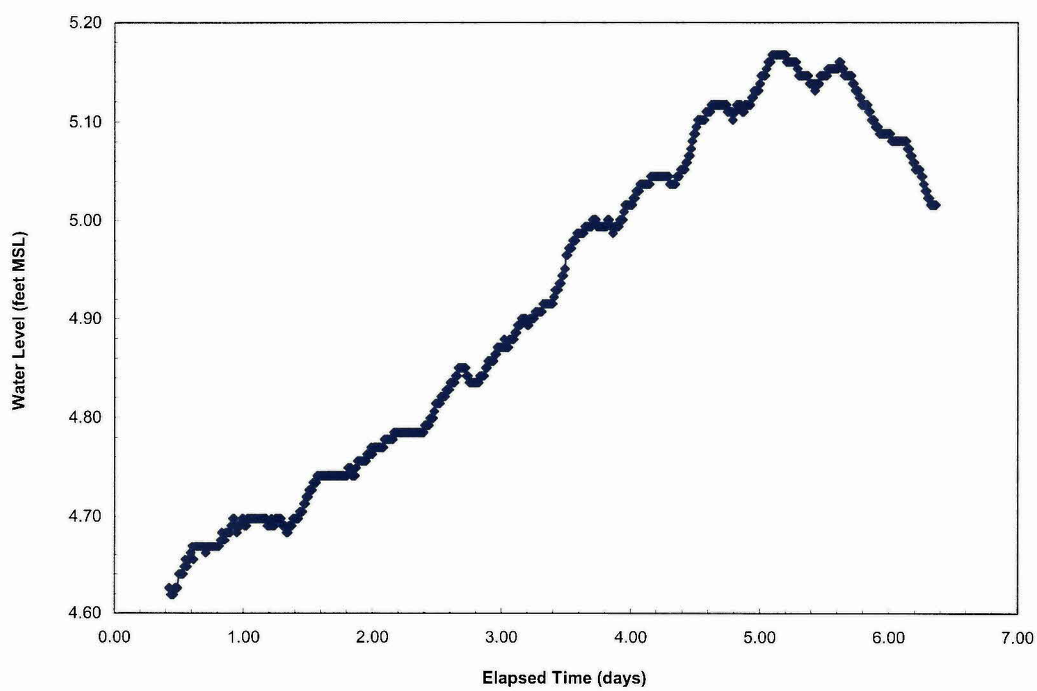


Figure C-28. Water levels illustrating recharge and tidal cycles in well MW-8D, February 16-22. 1995.

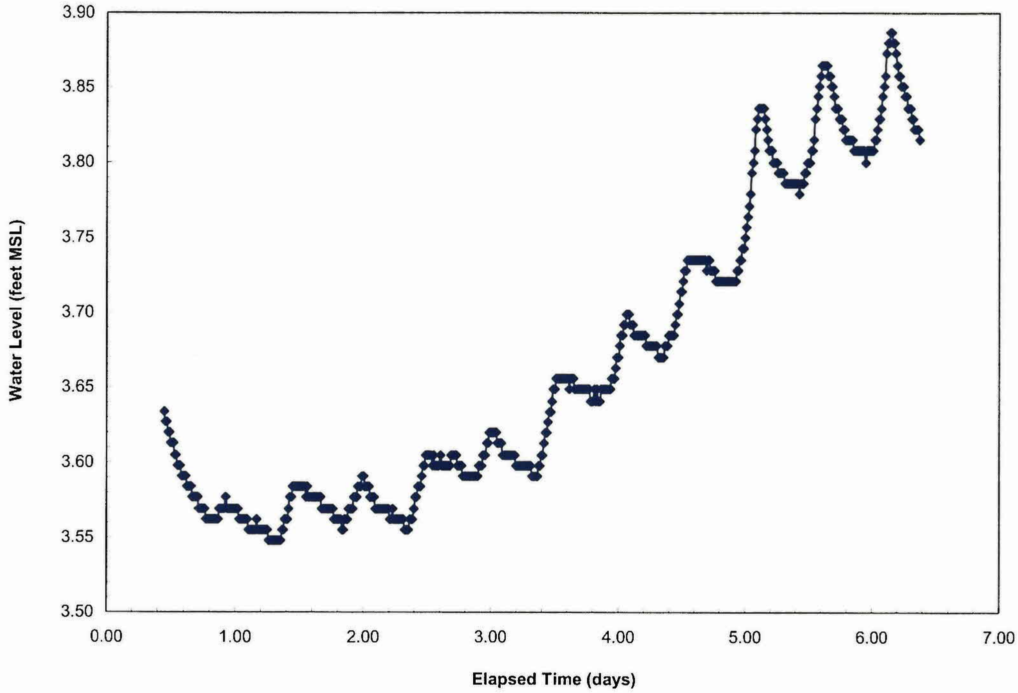


Figure C-29 Water levels illustrating recharge and tidal cycles in well MW-10D, February 16-22. 1995.

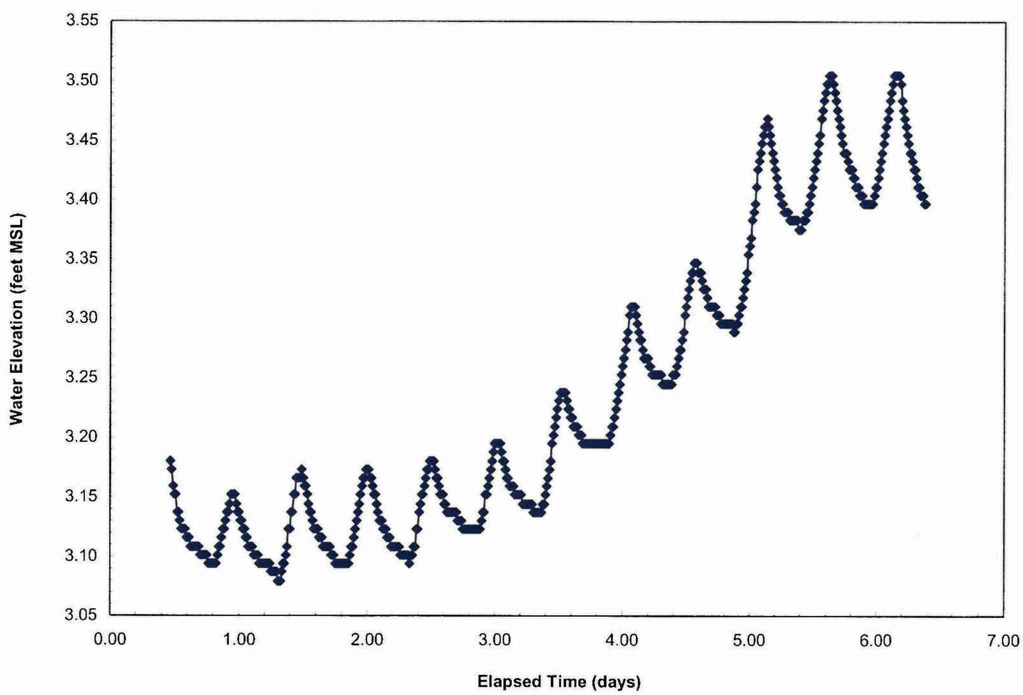


Figure C-30 Water levels illustrating recharge and tidal cycles in well MW-12D, February 16-22. 1995.

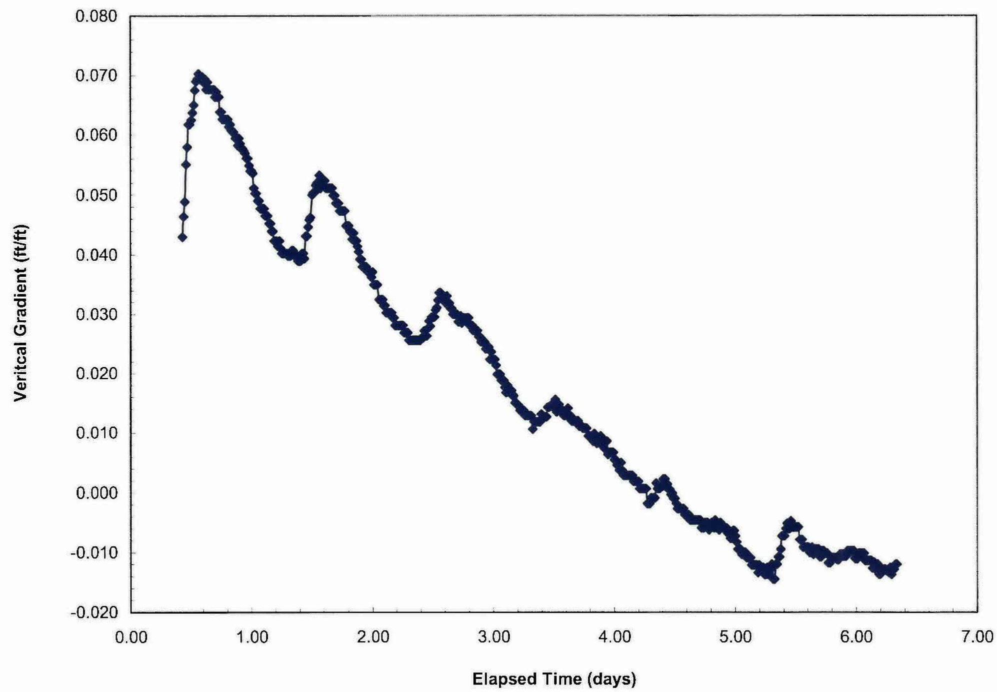


Figure C-31 Recharge and tidal effects on vertical gradient in cluster MW-8, February 16-22. 1995. Negative gradients indicate upward flow of ground water.

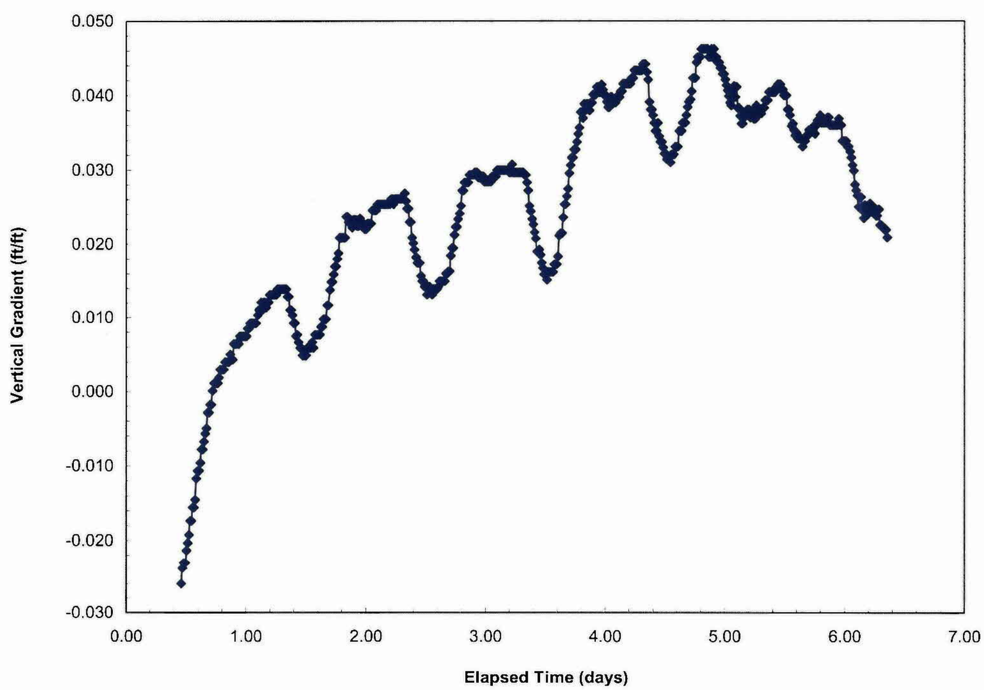


Figure C-32. Recharge and tidal effects on vertical gradient in cluster MW-10, February 16-22. 1995. Negative gradients indicate upward flow of ground water.

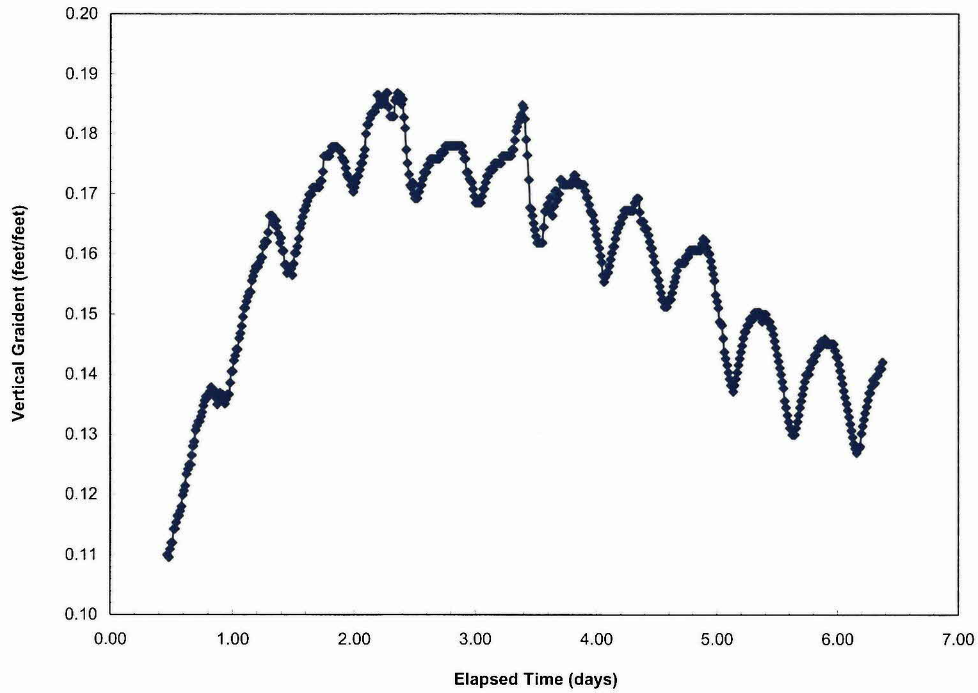


Figure C-33. Recharge and tidal effects on vertical gradient in cluster MW-12, February 16-22. 1995. Negative gradients indicate upward flow of ground water.

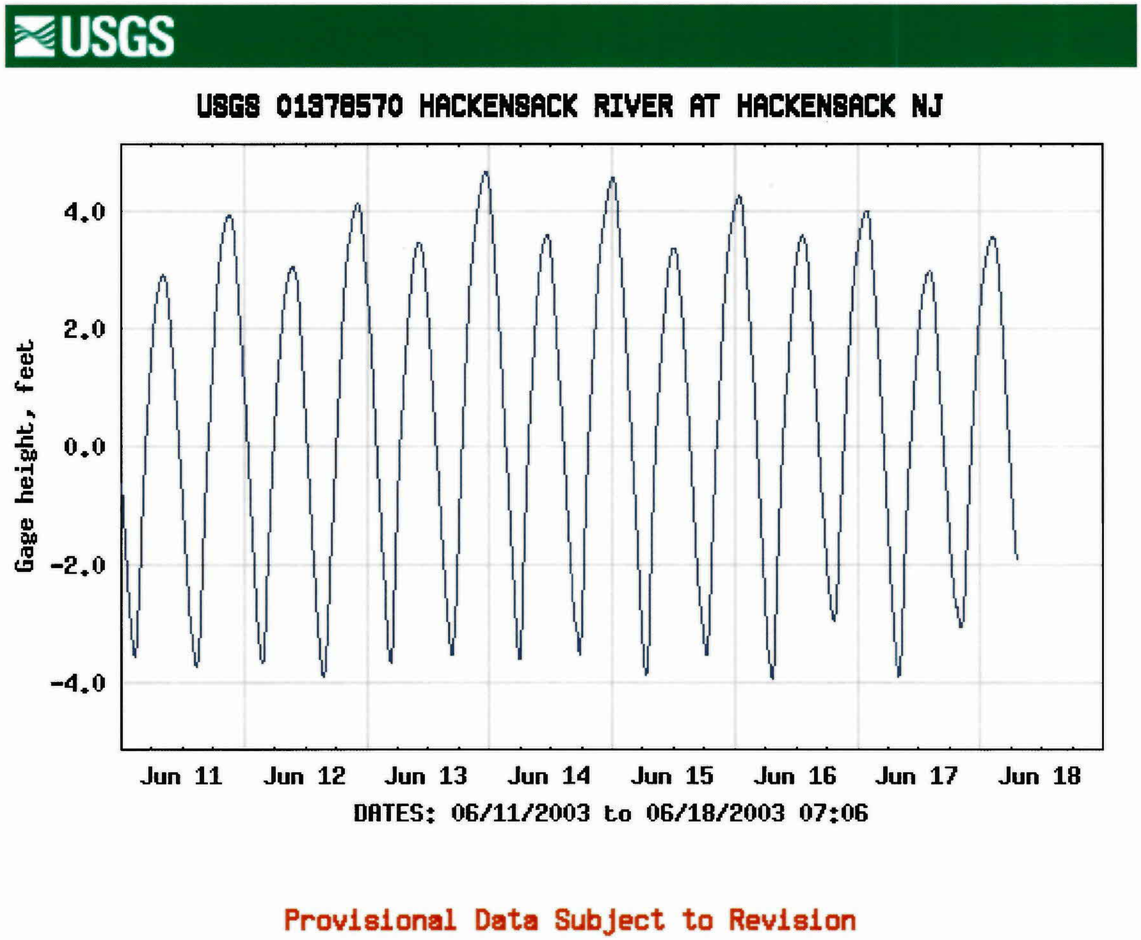


Figure C-34. Tidal record at the USGS gauging station for the Hackensack River at Hackensack, NJ. (Source: USGS 2003)

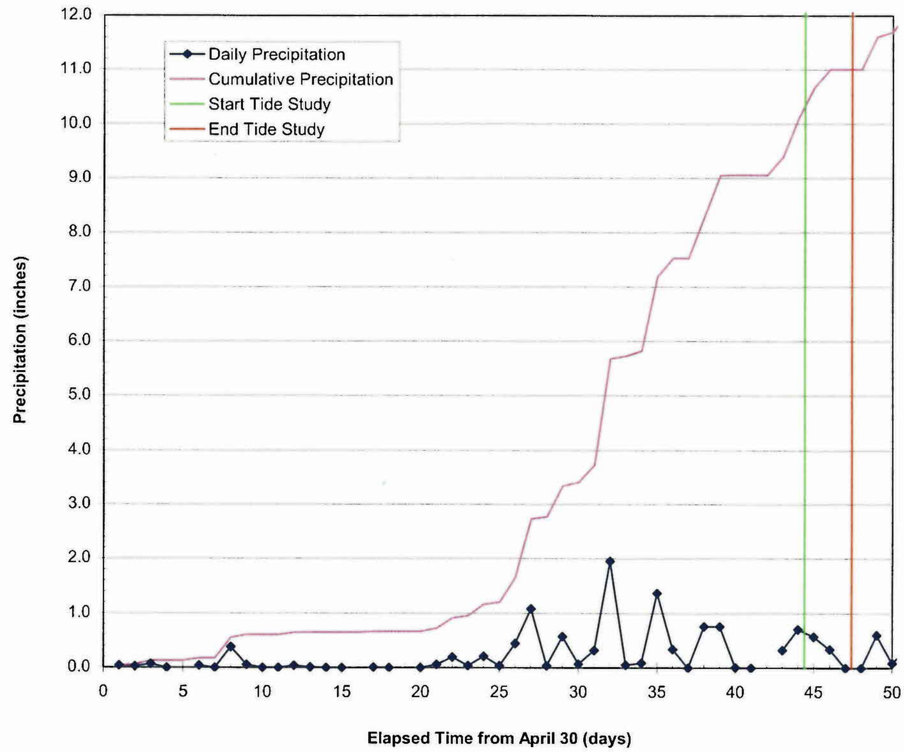


Figure C-35. Precipitation data for Teterboro Airport, NJ for May and June 2003 prior to the start of the June 2003 tidal study. (Source: NCDC 2003)

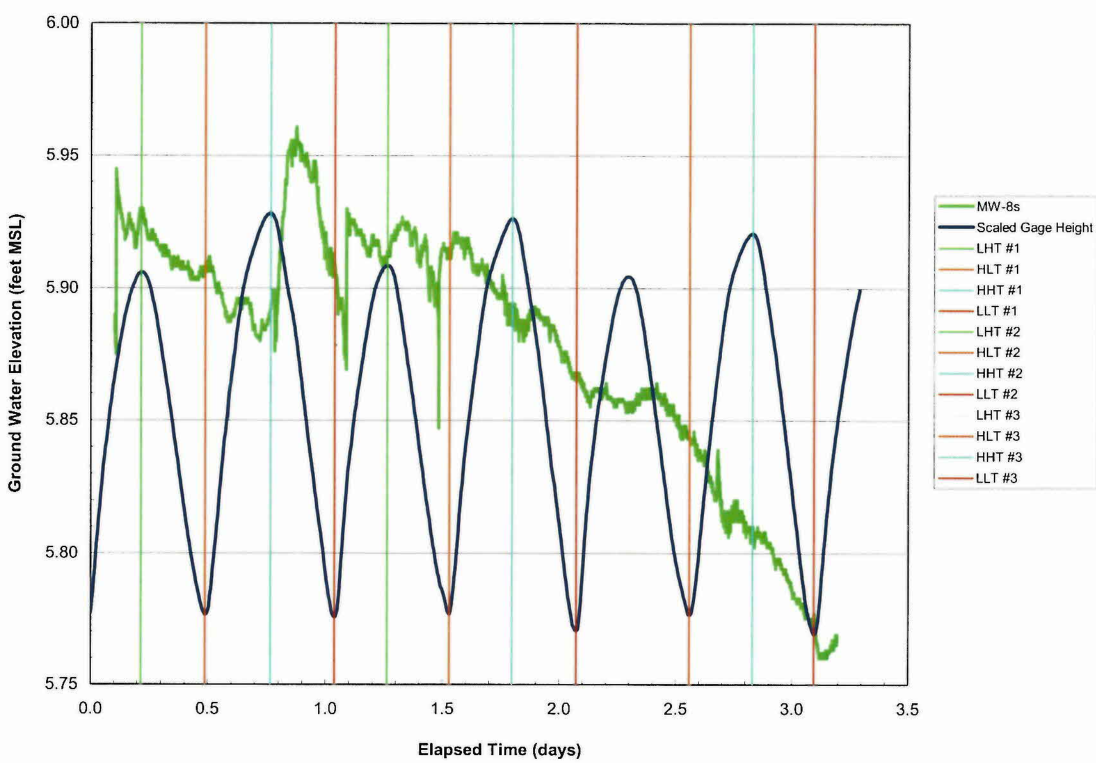


Figure C-36. Water levels in well MW-8S during the June 13-16, 2003 tidal study.

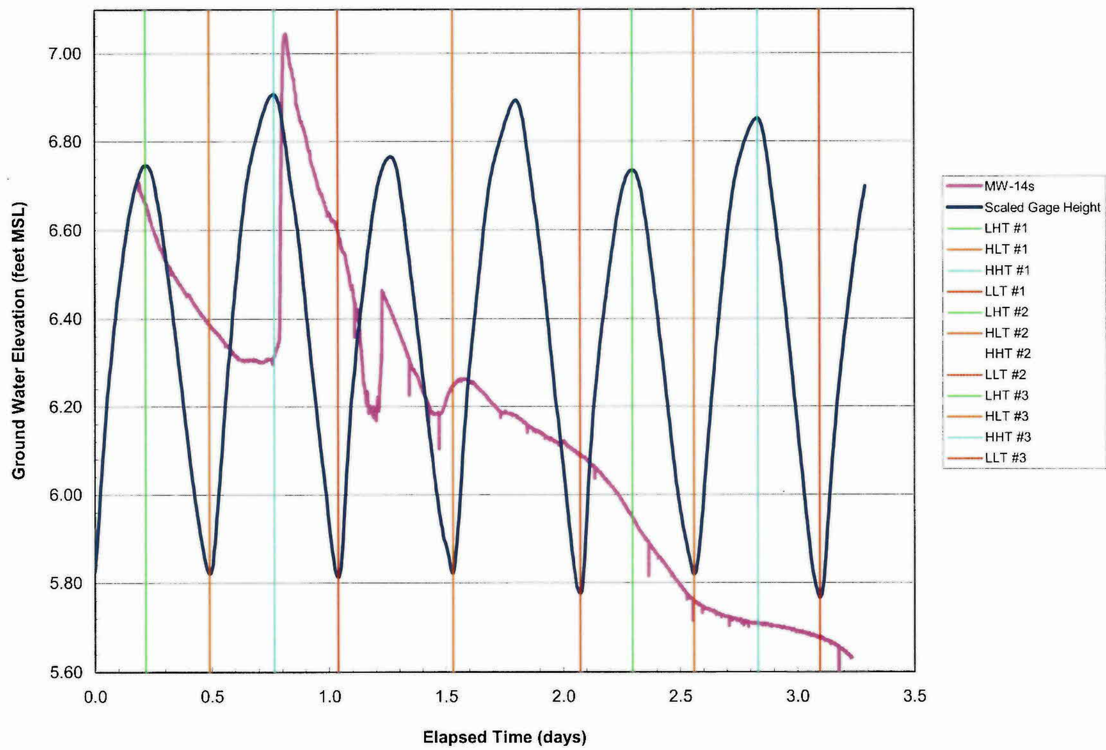


Figure C-37. Water levels in well MW-14S during the June 13-16, 2003 tidal study.

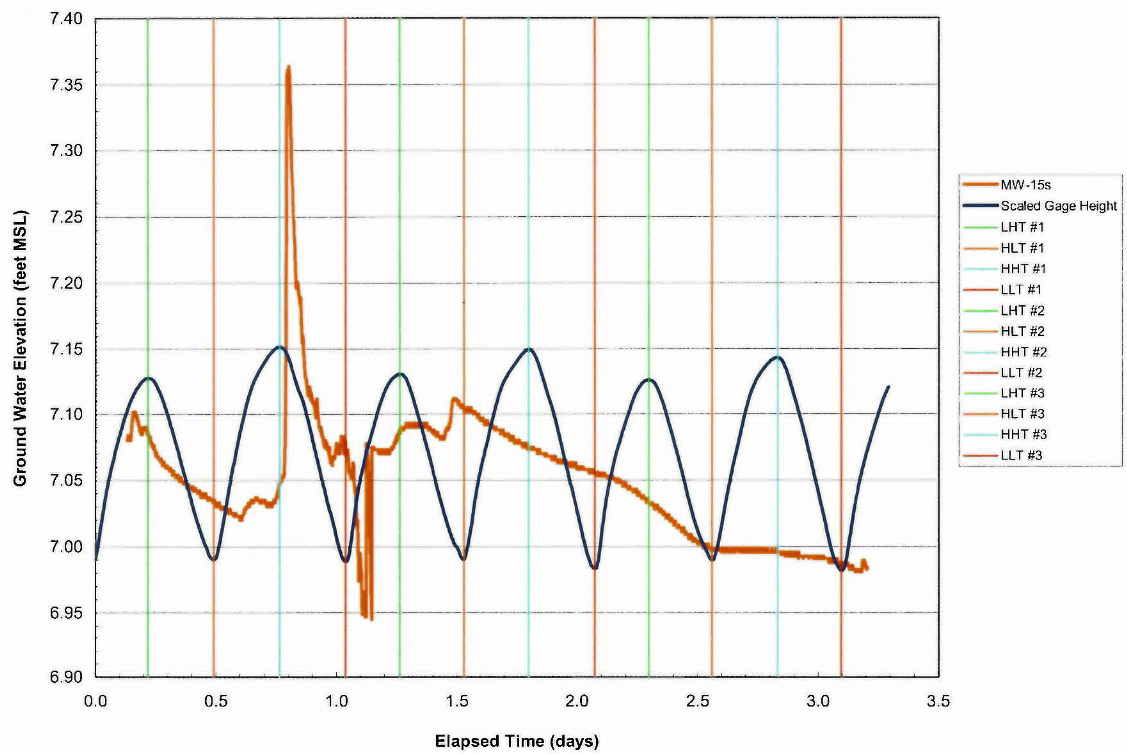


Figure C-38. Water levels in well MW-15S during the June 13-16, 2003 tidal study.

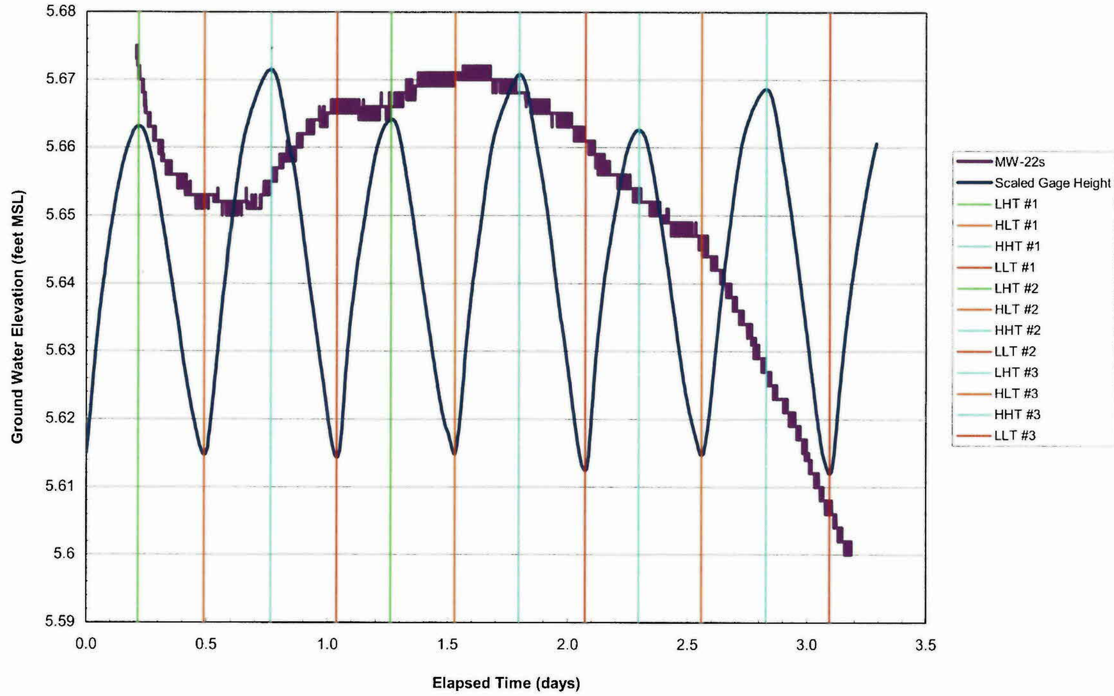


Figure C-39. Water levels in well MW-22S during the June 13-16, 2003 tidal study.

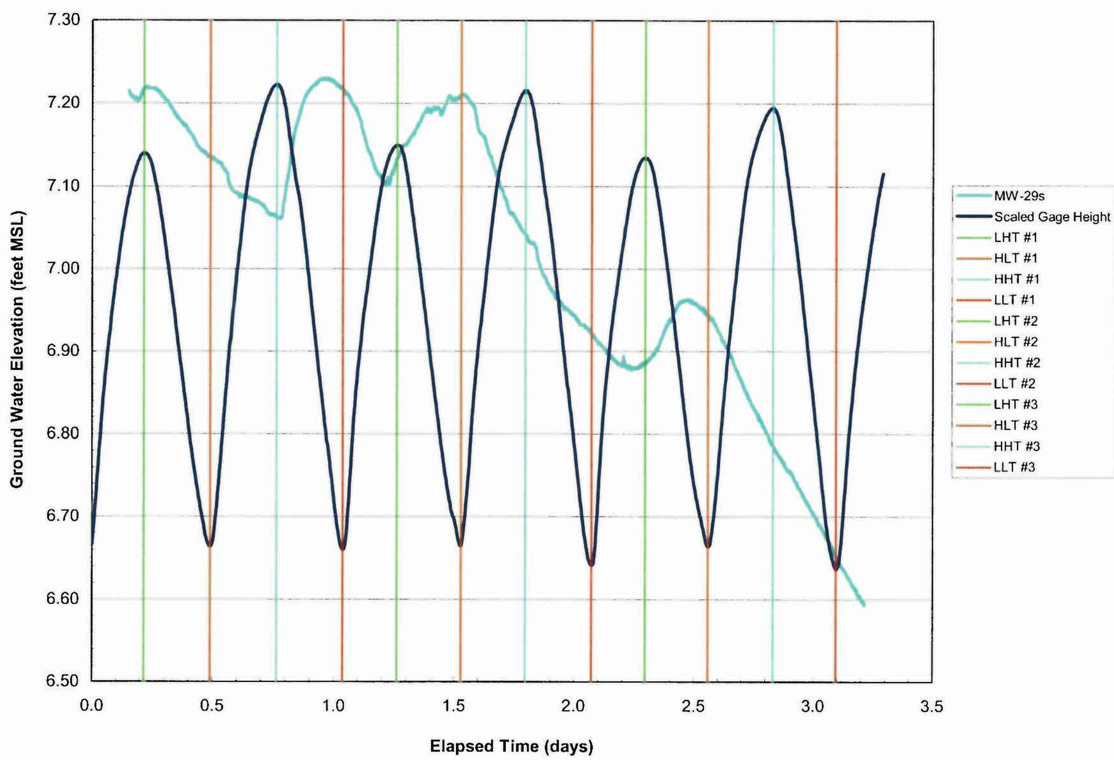


Figure C-40. Water levels in well MW-29S during the June 13-16, 2003 tidal study.

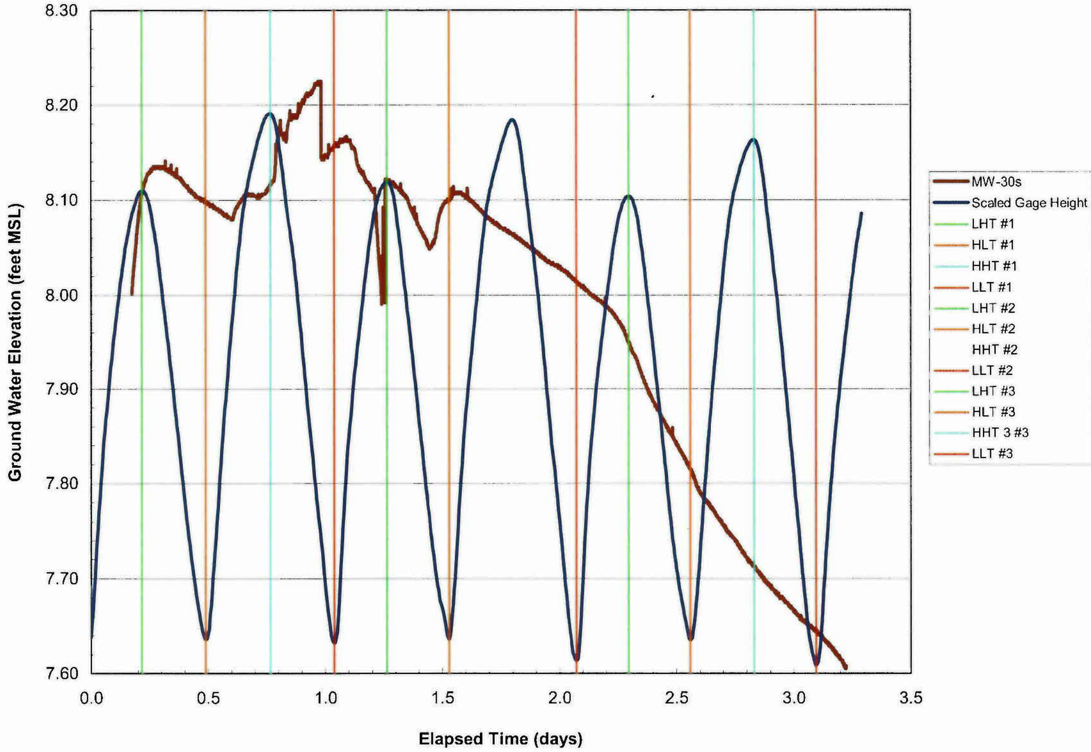


Figure C-41. Water levels in well MW-30S during the June 13-16, 2003 tidal study.

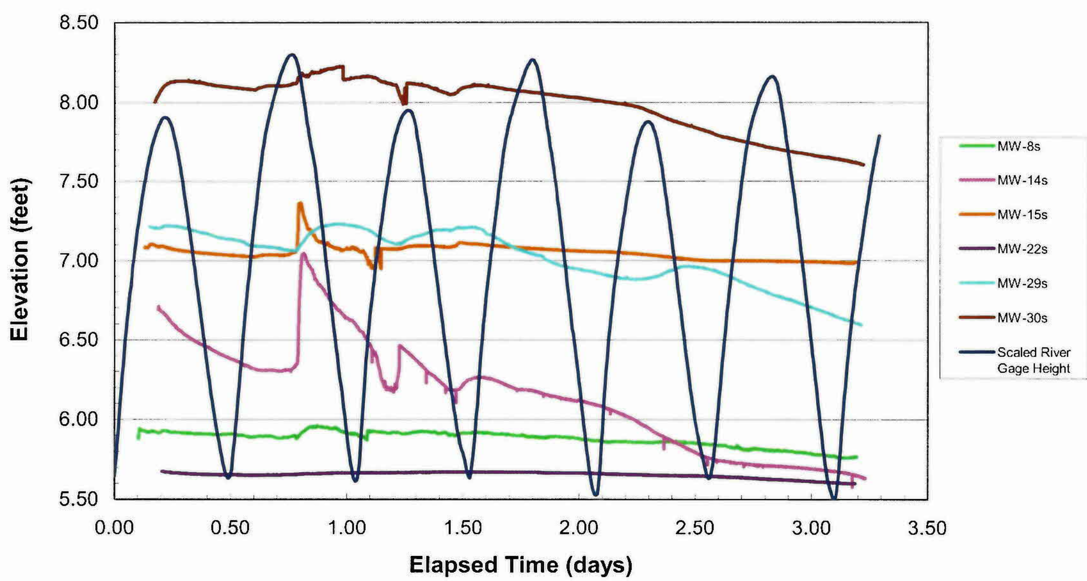


Figure C-42. Water levels in all shallow wells during the June 13-16, 2003 tidal study.

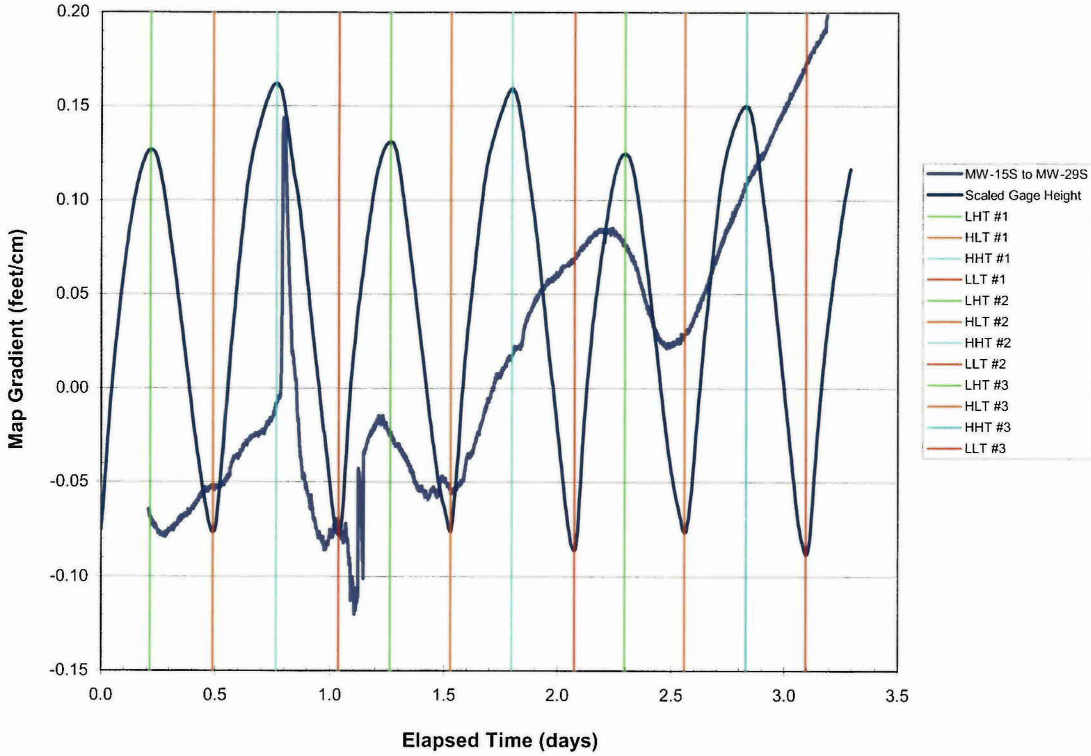


Figure C-43. Hydraulic gradient from MW-15S to MW-29S during the June 2003 tidal study. Negative gradients indicate flow toward MW-15S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

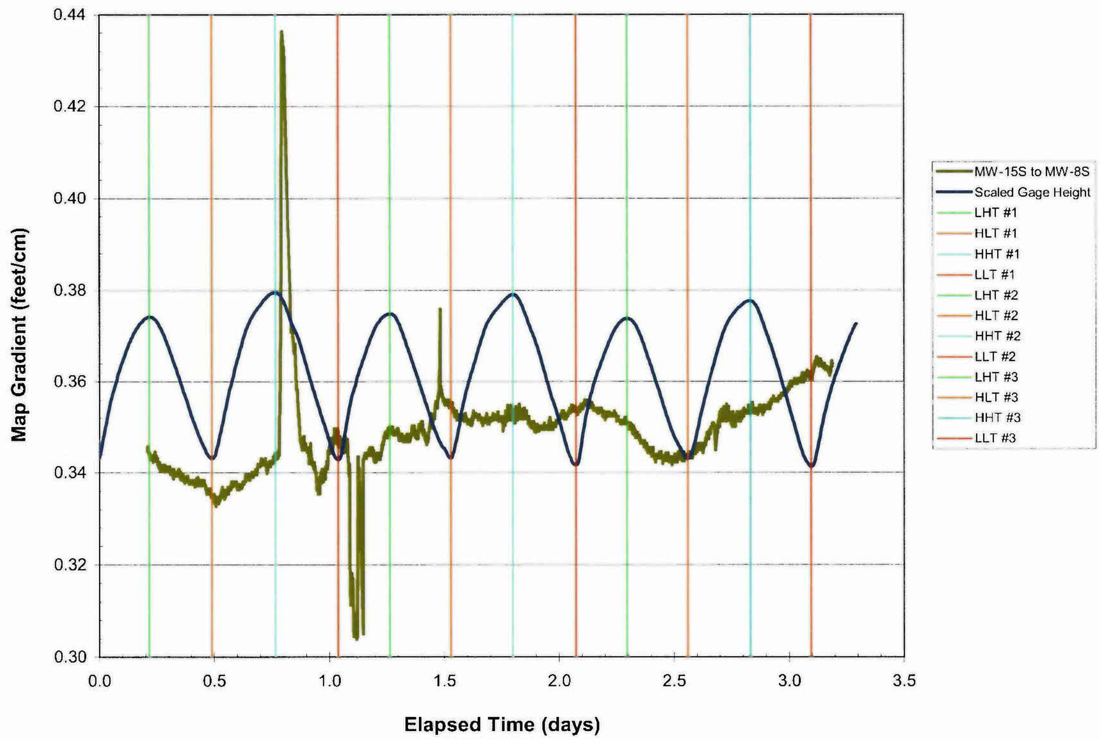


Figure C-44. Hydraulic gradient from MW-15S to MW-8S during the June 2003 tidal study. Negative gradients indicate flow toward MW-15S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

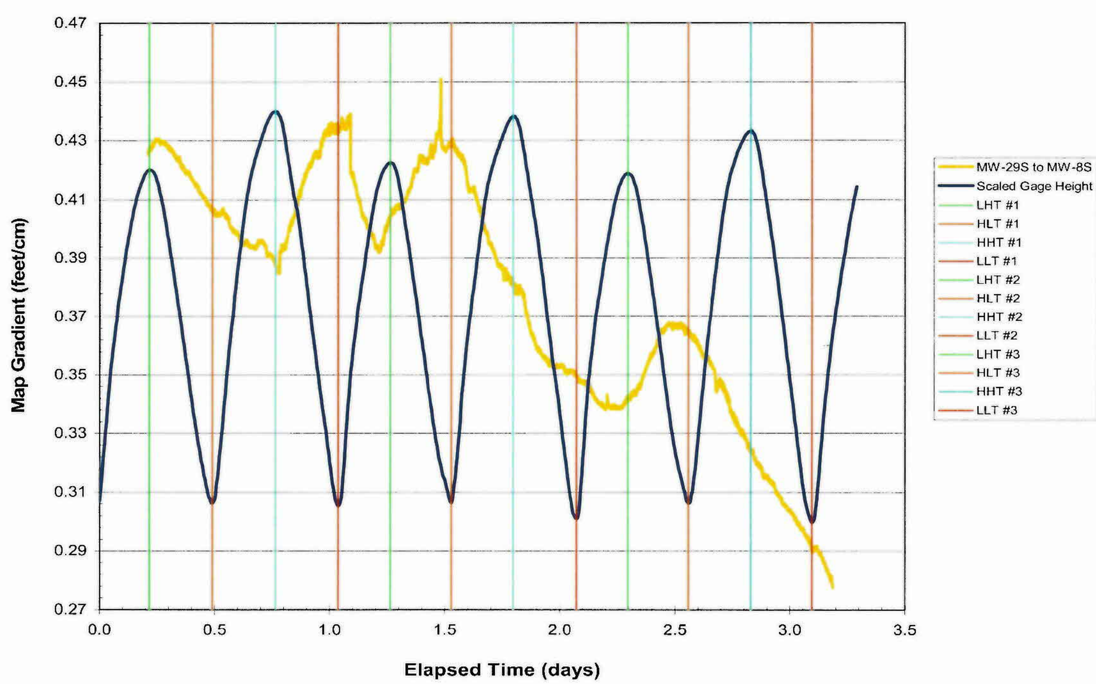


Figure C-45. Hydraulic gradient from MW-29S to MW-8S during the June 2003 tidal study. Negative gradients indicate flow toward MW-29S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

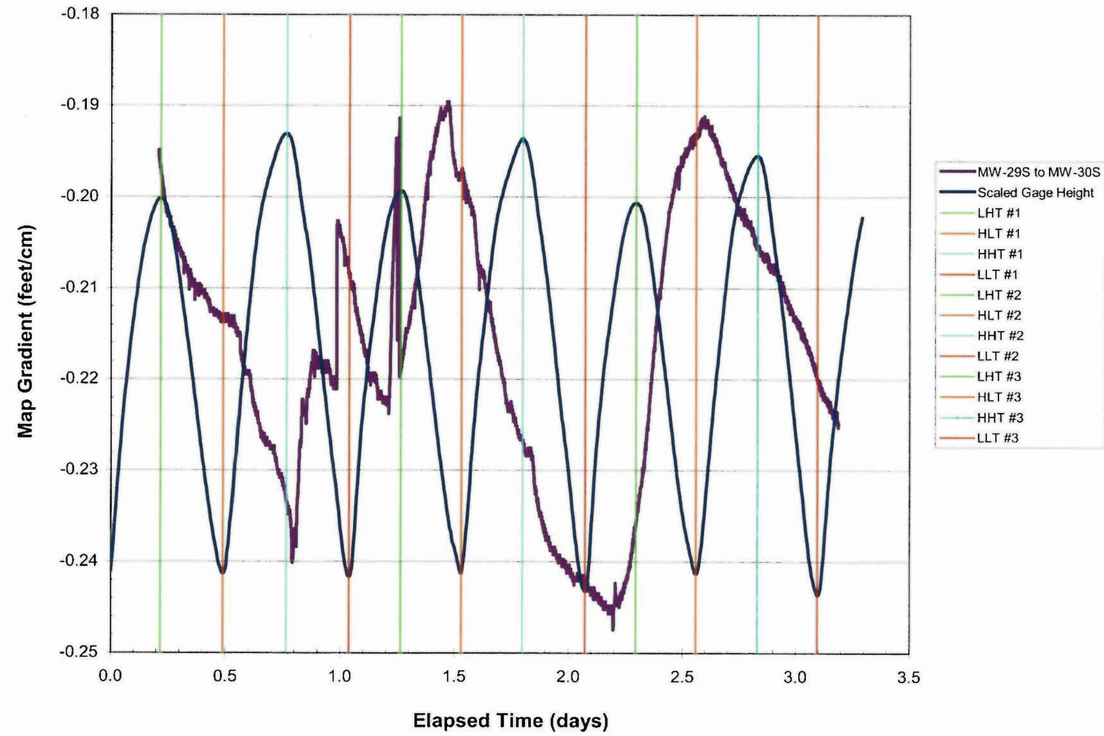


Figure C-46. Hydraulic gradient from MW-29S to MW-30S during the June 2003 tidal study. Negative gradients indicate flow toward MW-29S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

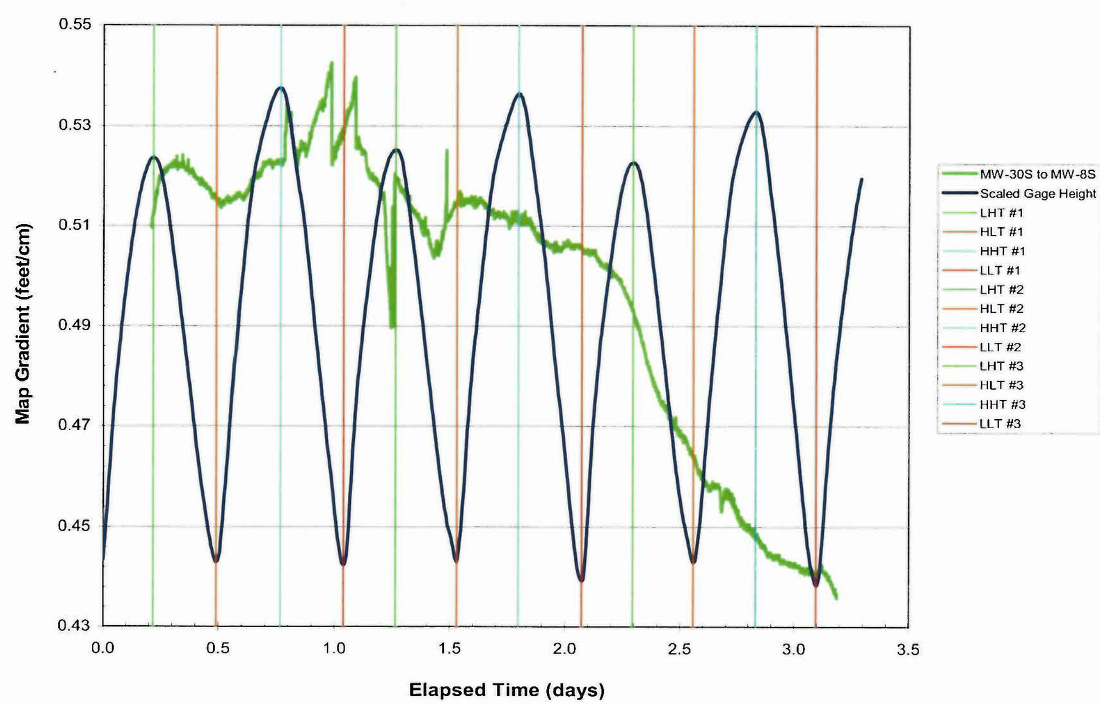


Figure C-47. Hydraulic gradient from MW-30S to MW-8S during the June 2003 tidal study. Negative gradients indicate flow toward MW-30S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

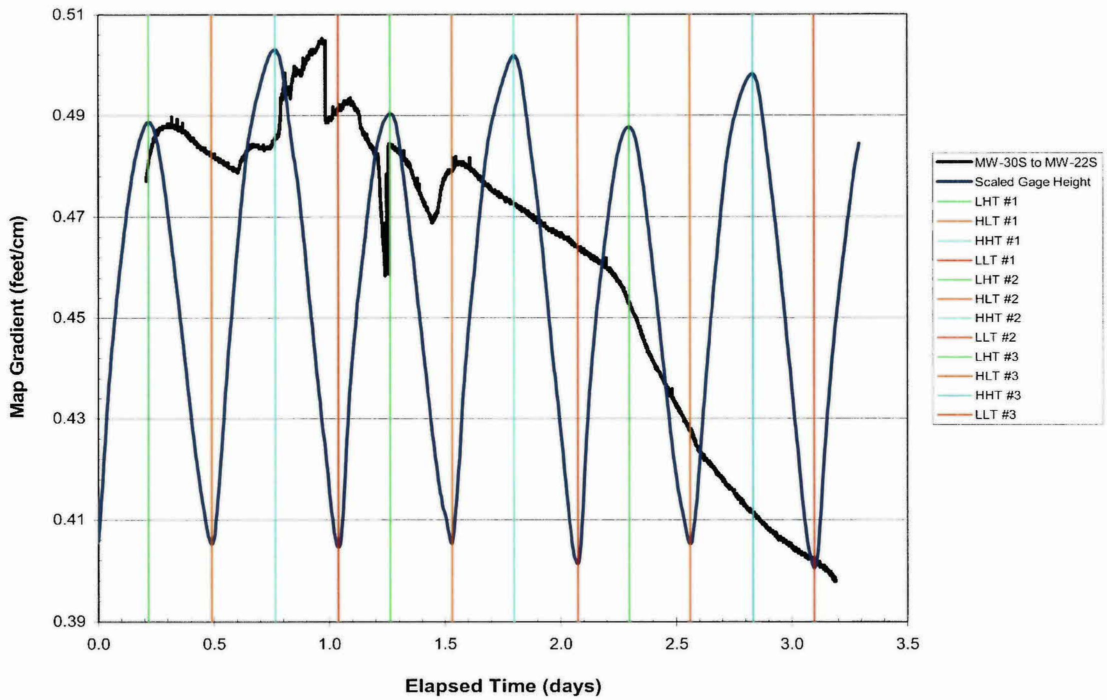


Figure C-48. Hydraulic gradient from MW-30S to MW-22S during the June 2003 tidal study. Negative gradients indicate flow toward MW-30S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

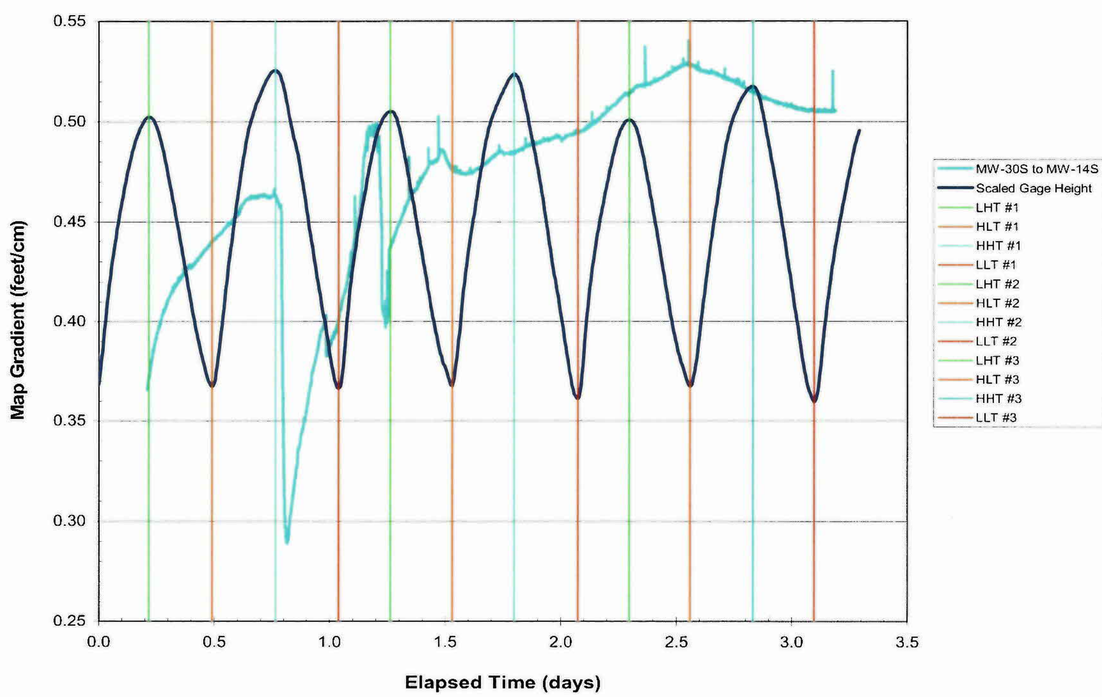


Figure C-49. Hydraulic gradient from MW-30S to MW-14S during the June 2003 tidal study. Negative gradients indicate flow toward MW-30S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

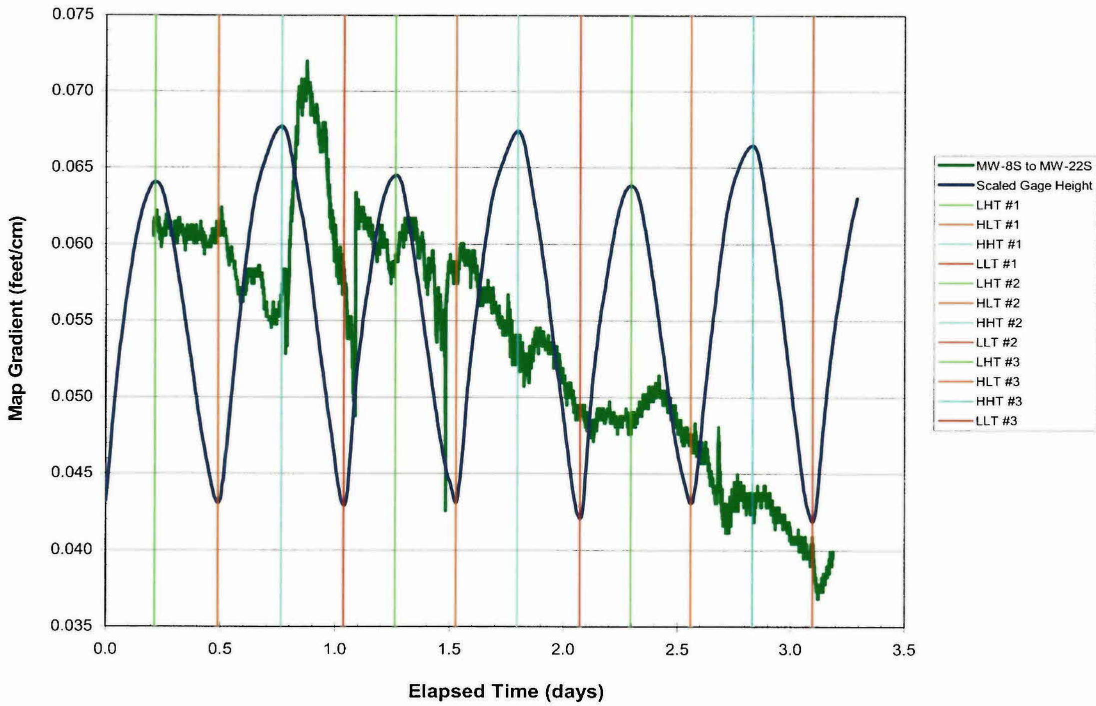


Figure C-50. Hydraulic gradient from MW-8S to MW-22S during the June 2003 tidal study. Negative gradients indicate flow toward MW-8S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

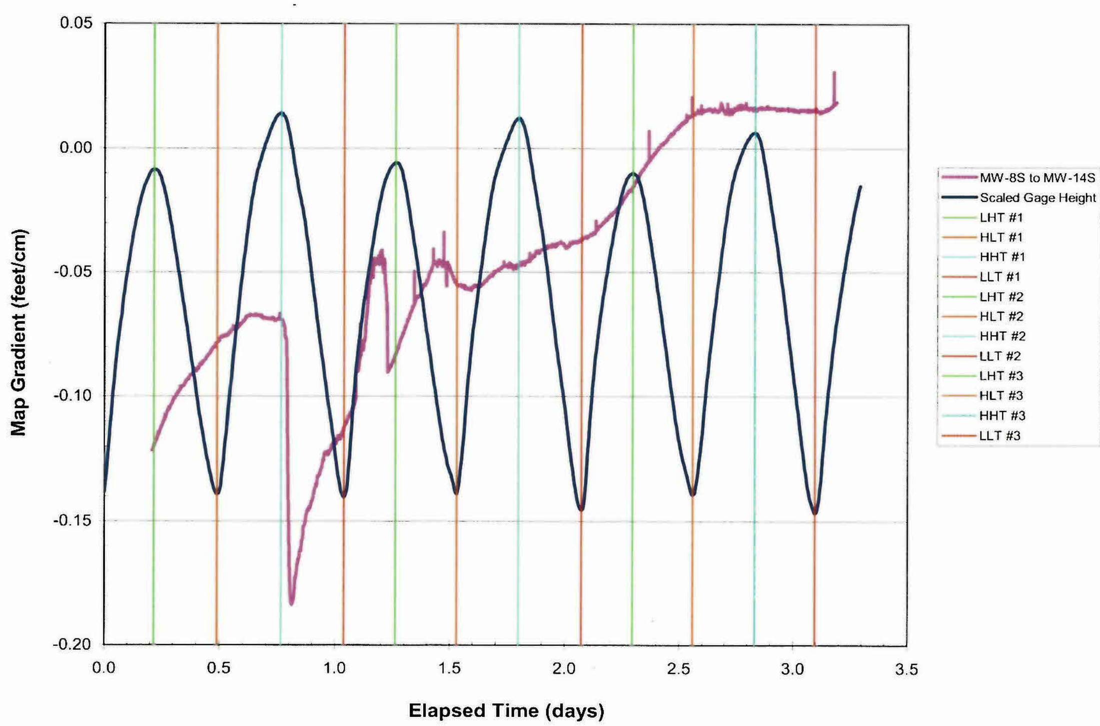


Figure C-51. Hydraulic gradient from MW-8S to MW-14S during the June 2003 tidal study. Negative gradients indicate flow toward MW-8S. Map gradients may be converted to actual gradients by dividing by the map scale conversion (39.37 feet/cm).

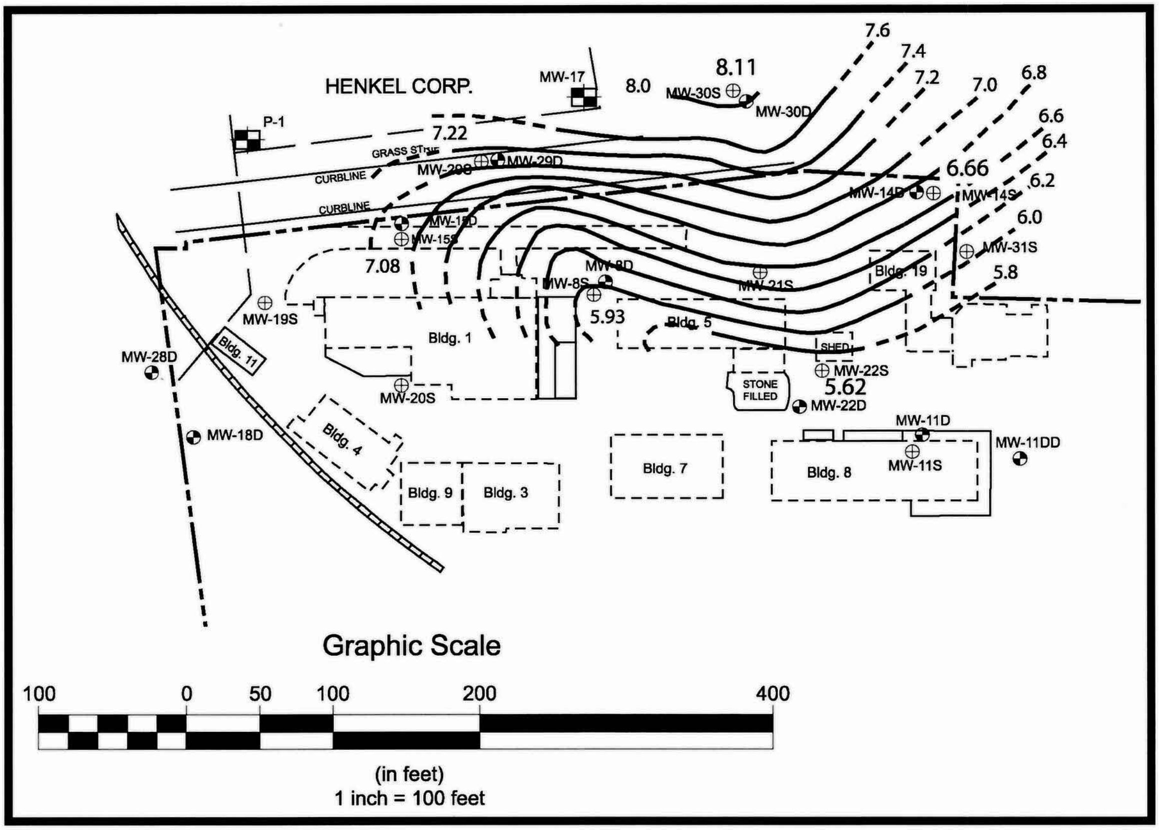


Figure C-52. Water table map for the northwest portion of the site for June 13, 2003 at 10:12 AM. Elapsed time is 0.22083 days, approximate time of the first lower high tide.

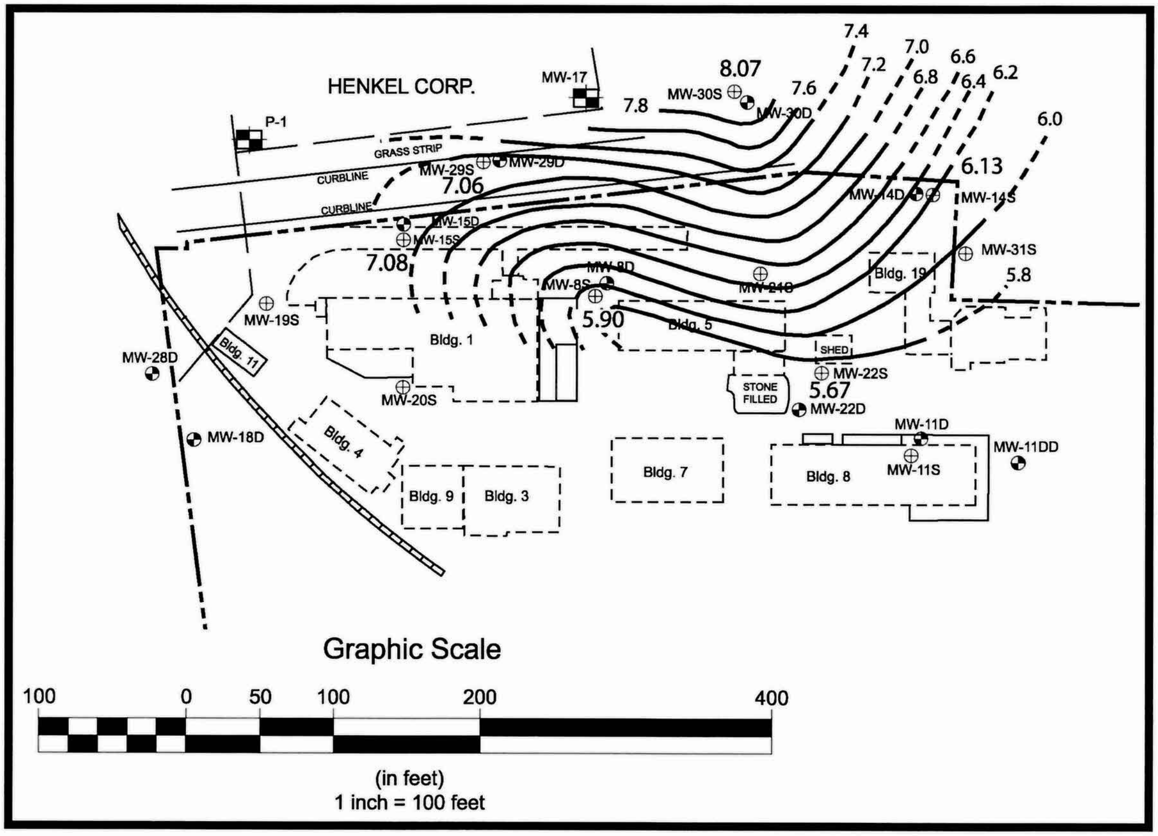


Figure C-53. Water table map for the northwest portion of the site for June 14, 2003 at 11:25 PM. Elapsed time is 1.76736 days, approximate time of the second higher high tide.

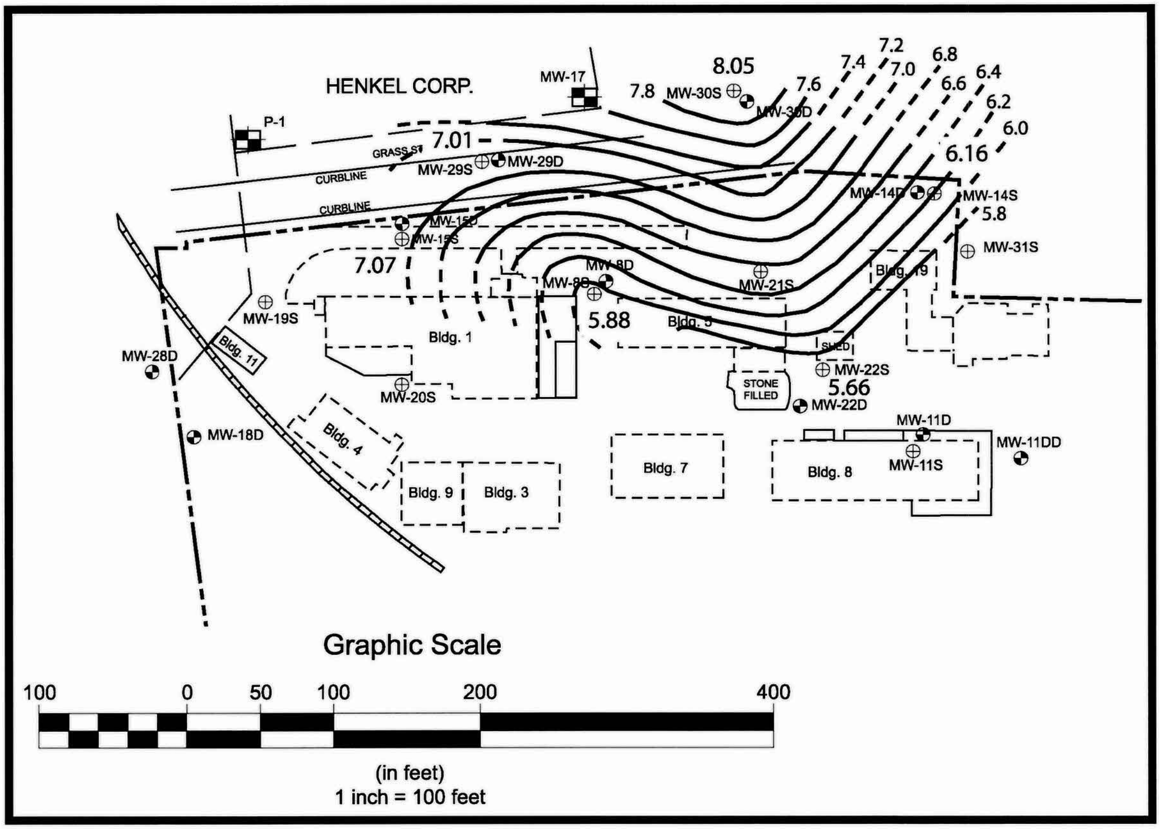


Figure C-54. Water table map for the northwest portion of the site for June 15, 2003 at 1:24 AM. Elapsed time is 1.85000 days, an intermediate time between the second higher high tide and the second lower low tide.

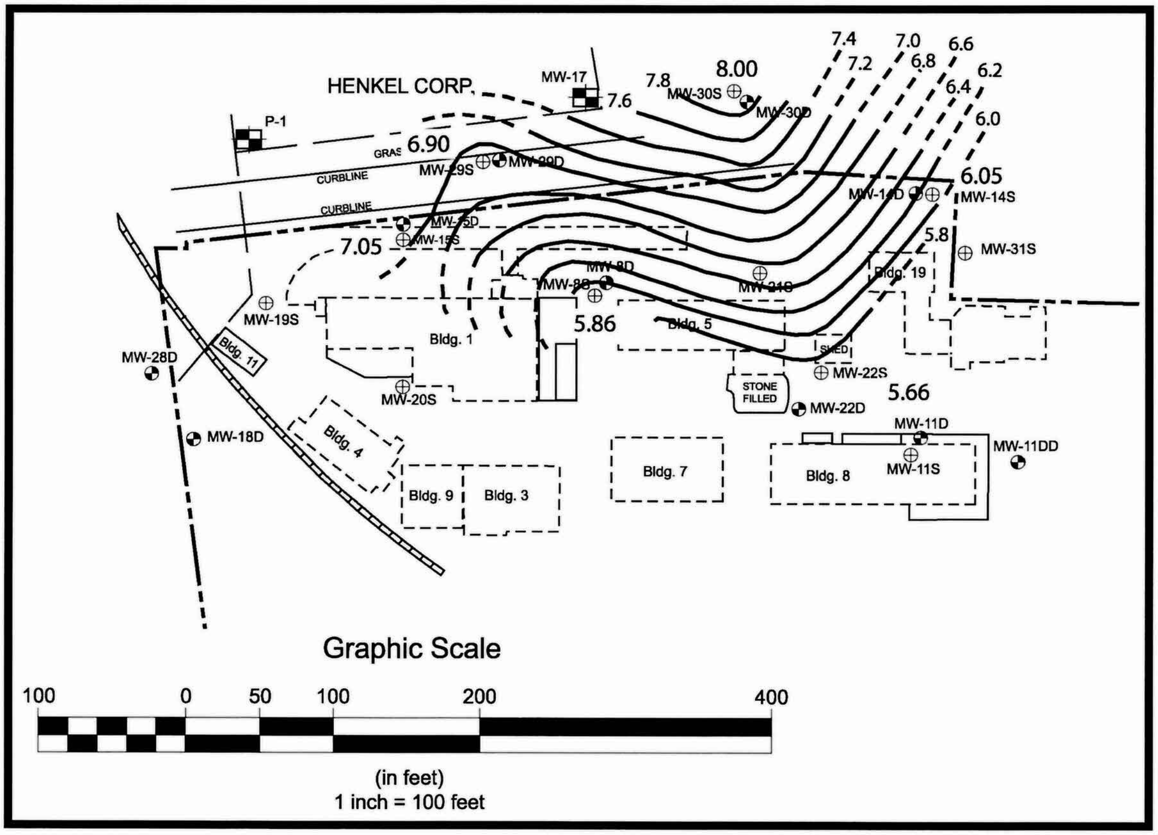


Figure C-55. Water table map for the northwest portion of the site for June 15, 2003 at 8:32 AM. Elapsed time is 2.14722 days, approximate time of the second lower low tide.

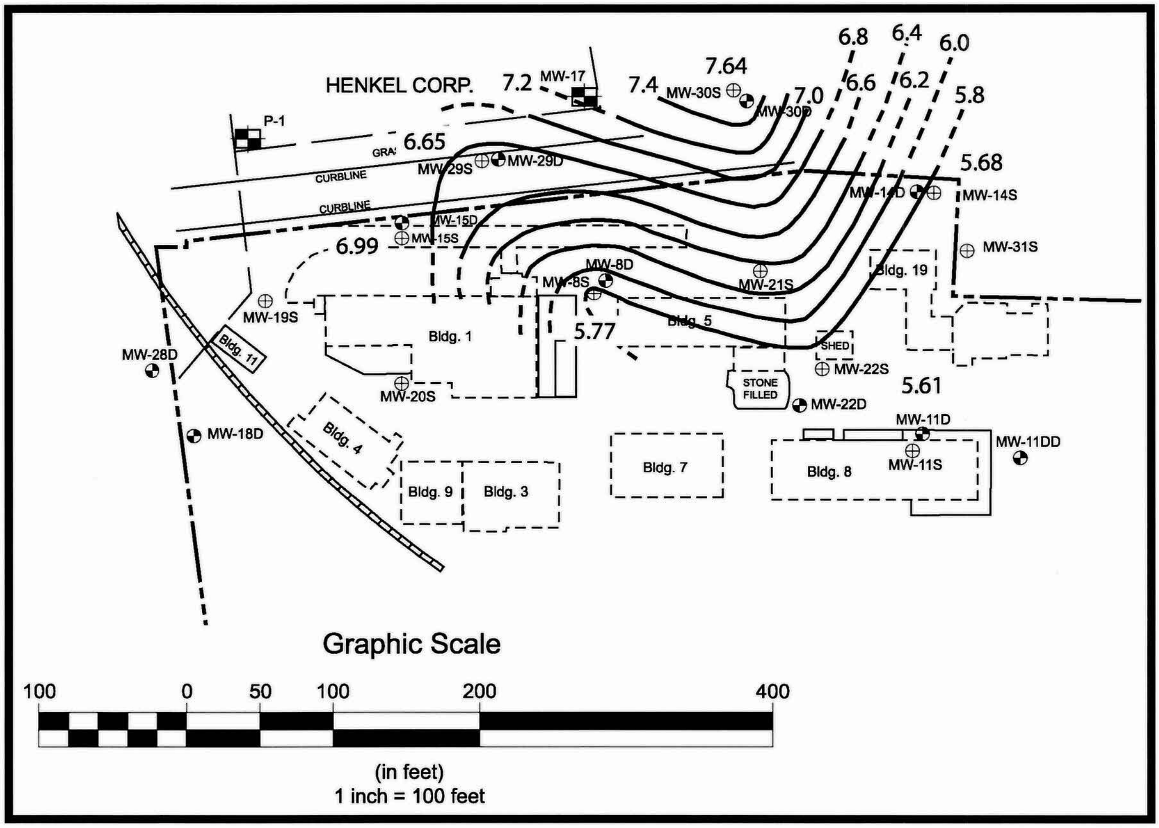


Figure C-56. Water table map for the northwest portion of the site for June 16, 2003 at 7:18 AM. Elapsed time is 3.09583 days, approximate time of the third lower low tide.

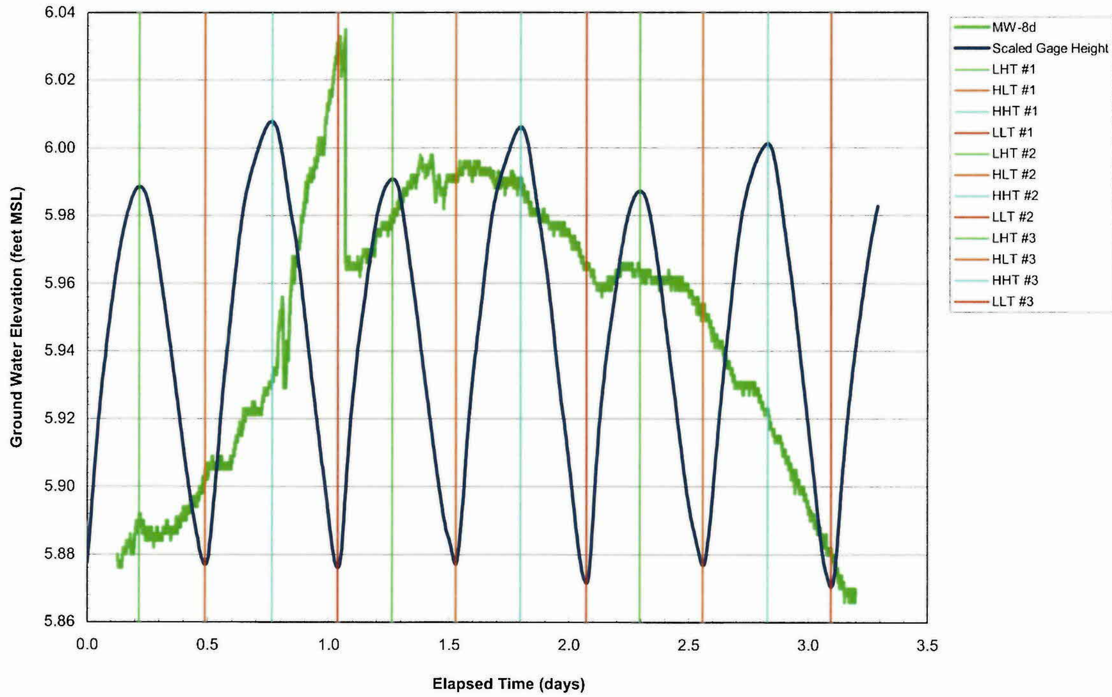


Figure C-57. Water levels in well MW-8D during the June 13-16, 2003 tidal study.

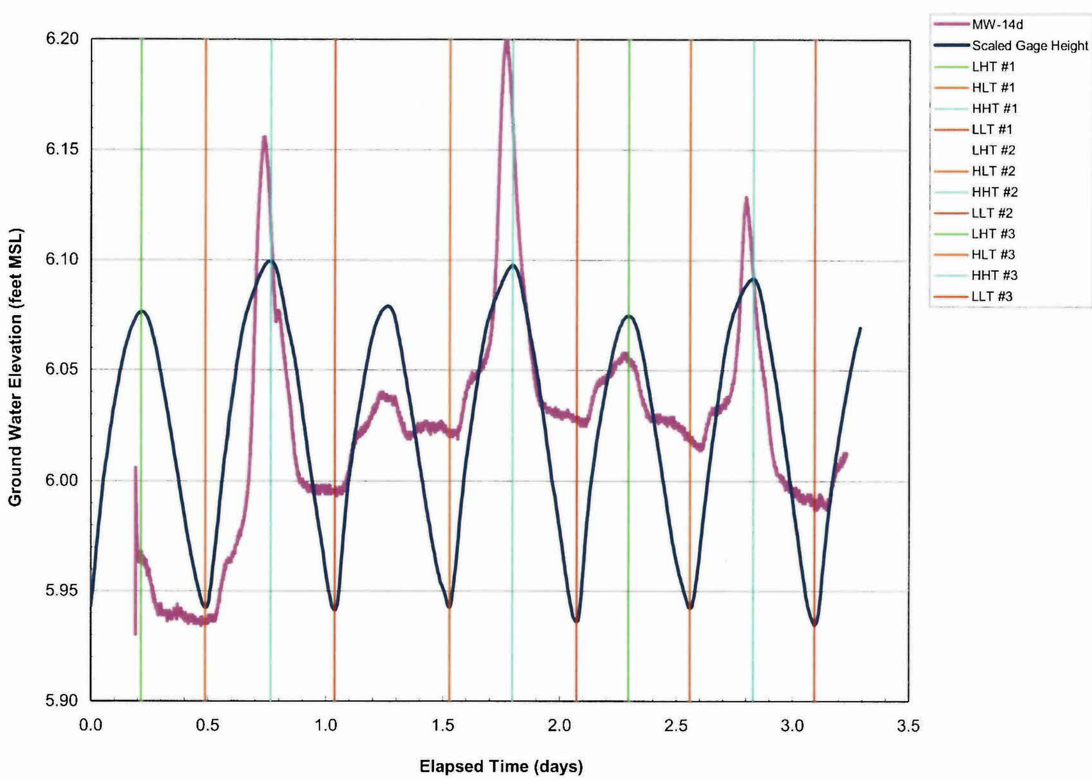


Figure C-58. Water levels in well MW-14D during the June 13-16, 2003 tidal study.

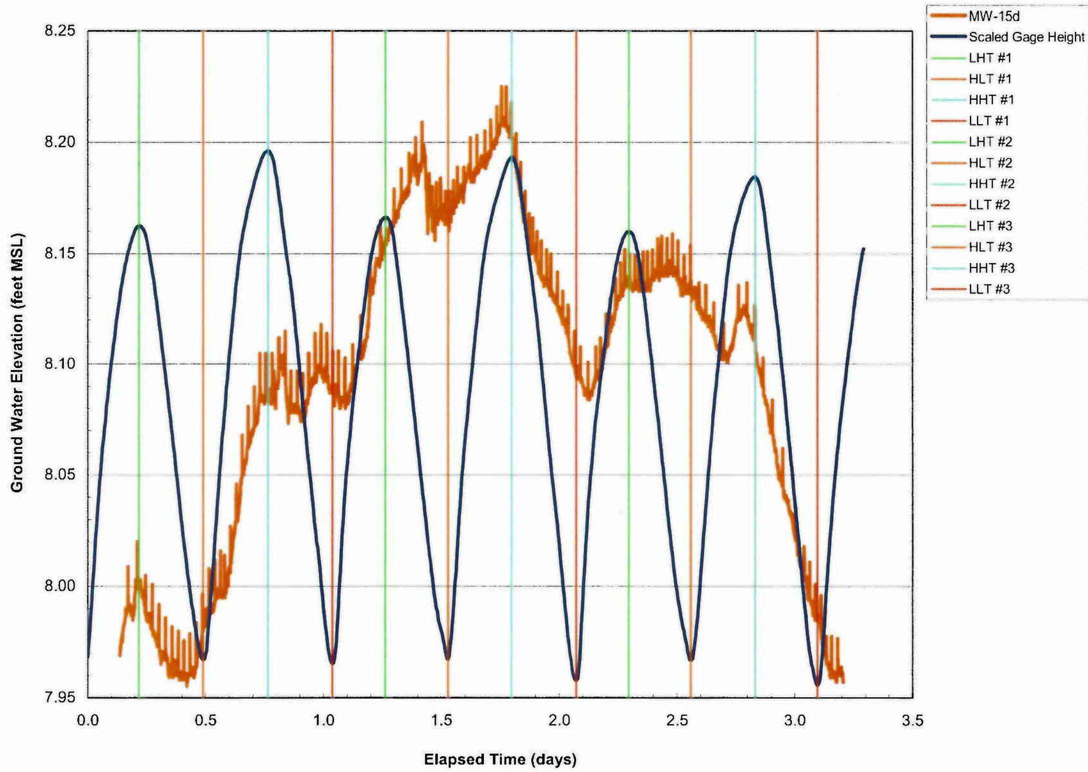


Figure C-59. Water levels in well MW-15D during the June 13-16, 2003 tidal study.

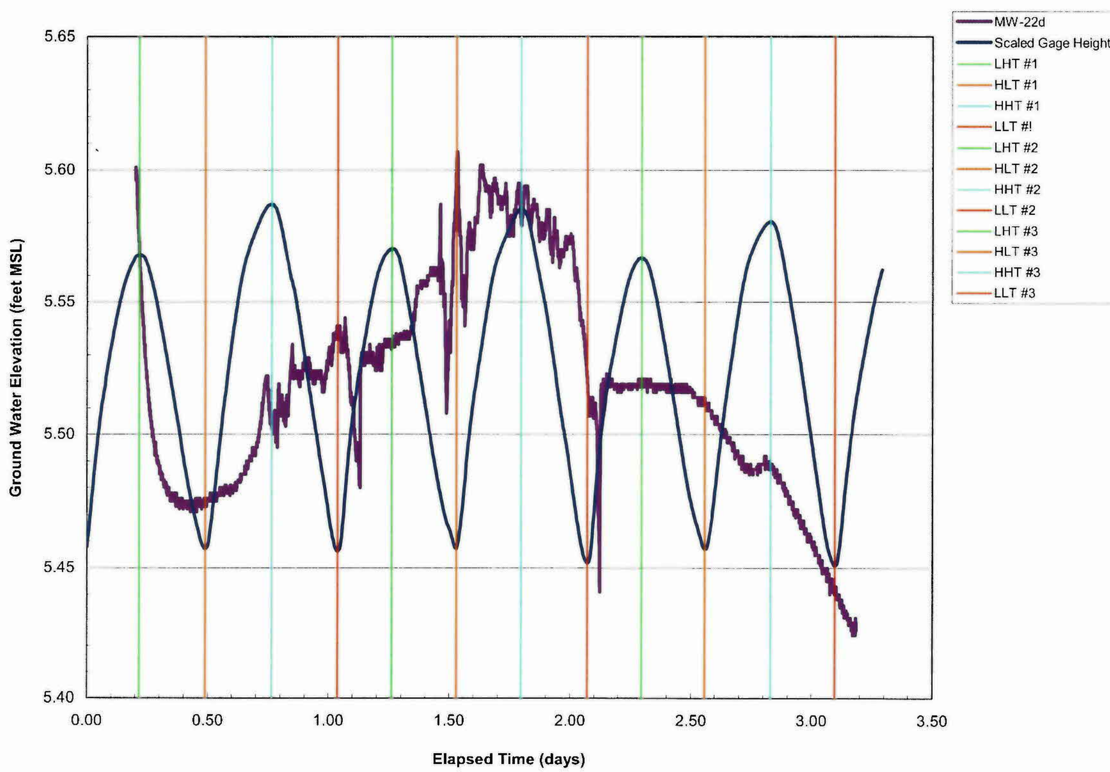


Figure C-60. Water levels in well MW-22D during the June 13-16, 2003 tidal study.

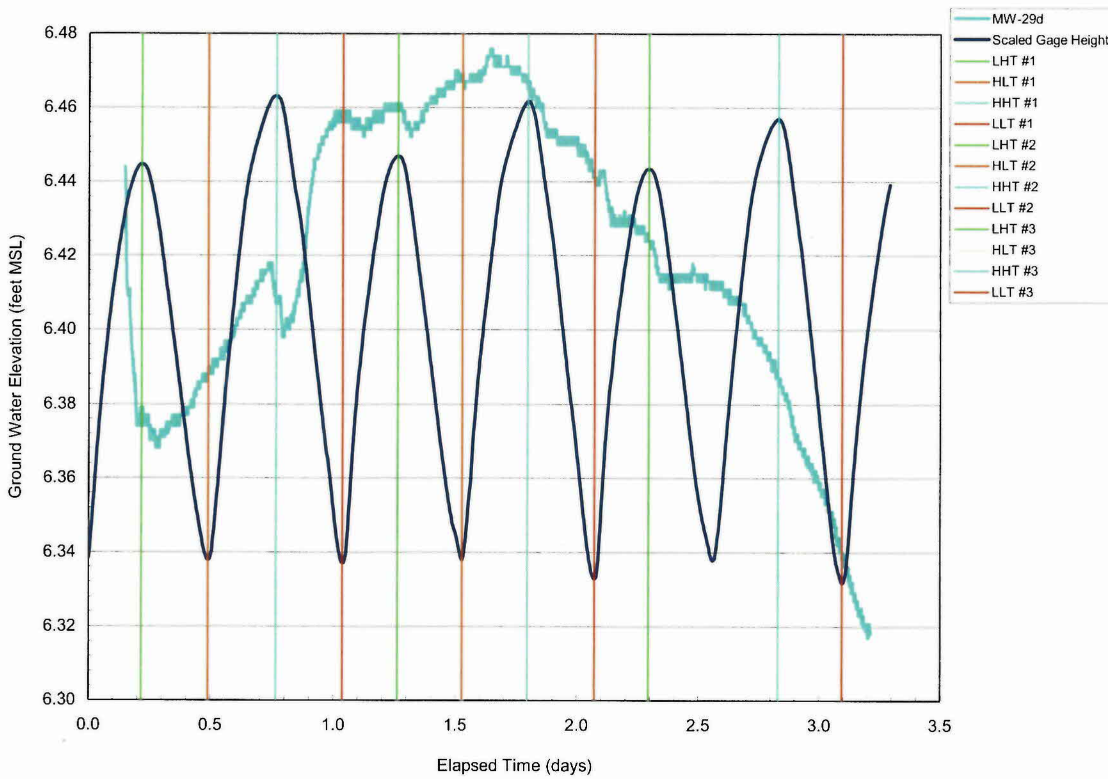


Figure C-61. Water levels in well MW-29D during the June 13-16, 2003 tidal study.

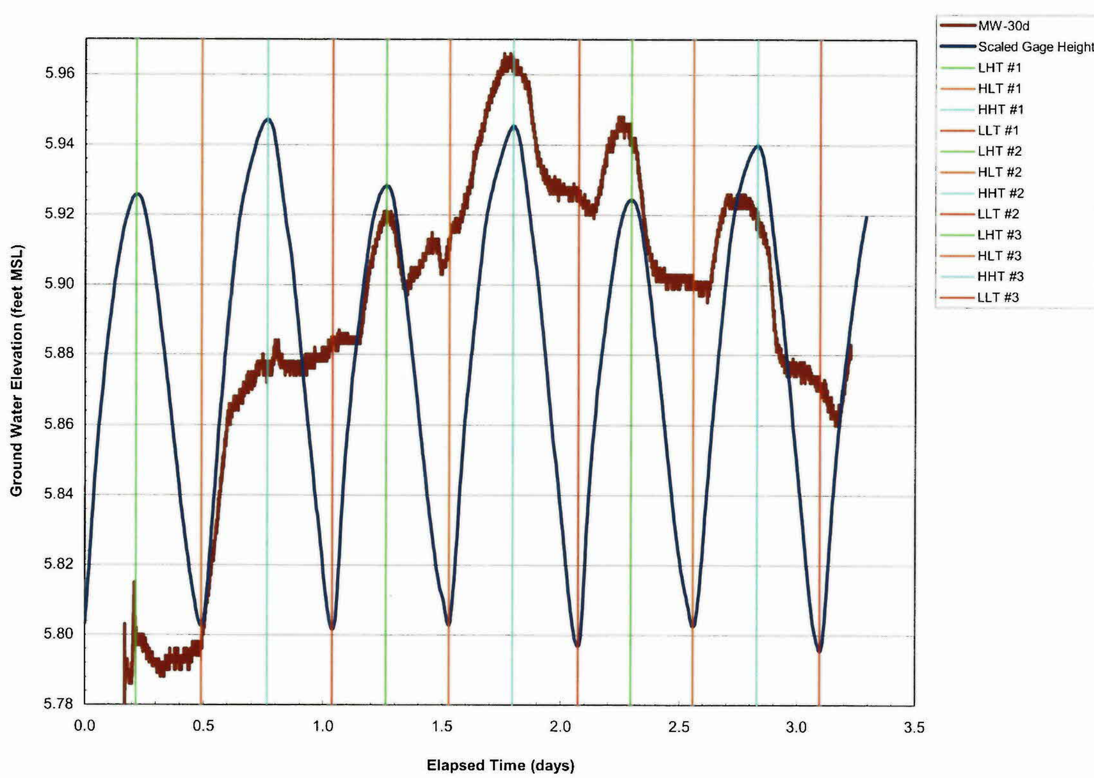


Figure C-62. Water levels in well MW-30D during the June 13-16, 2003 tidal study.

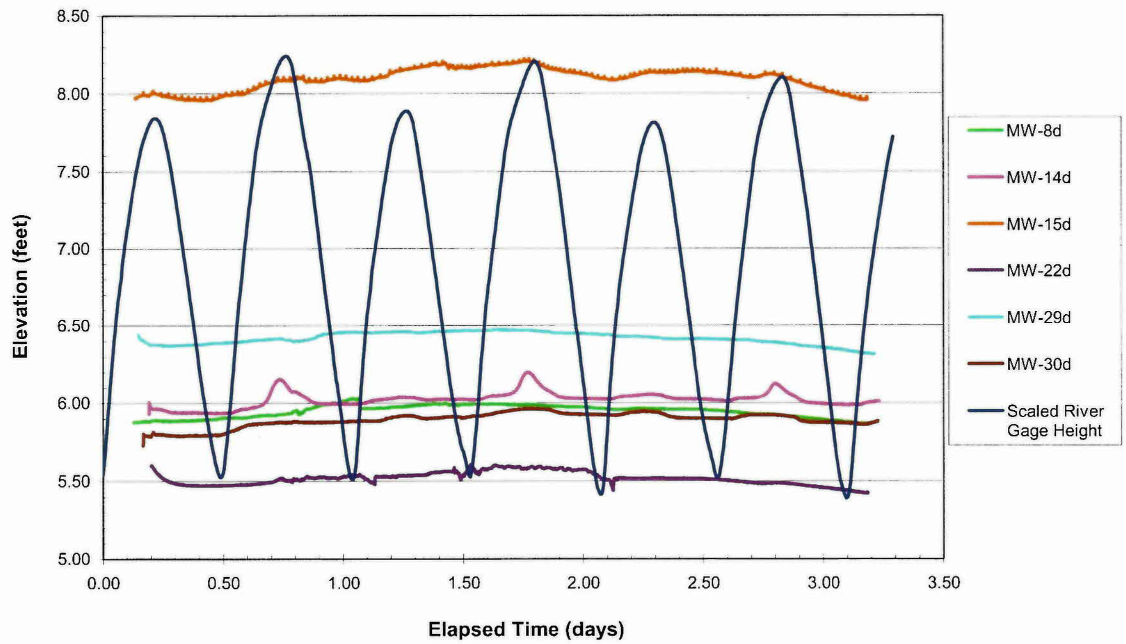


Figure C-63. Water levels in all D-wells during the June 13-16, 2003 tidal study.

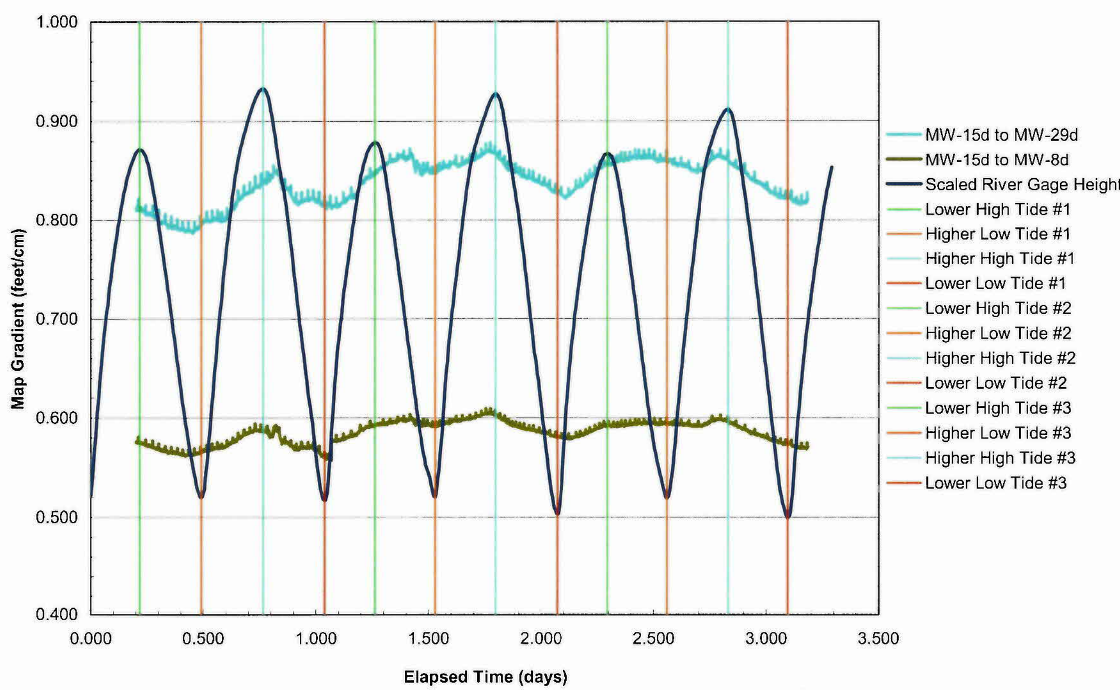


Figure C-64. Map gradients for ground water levels between MW-15D and MW-8D and MW-29D during the June 2003 tidal study. Positive gradients indicate flow toward the second well listed in the pair.

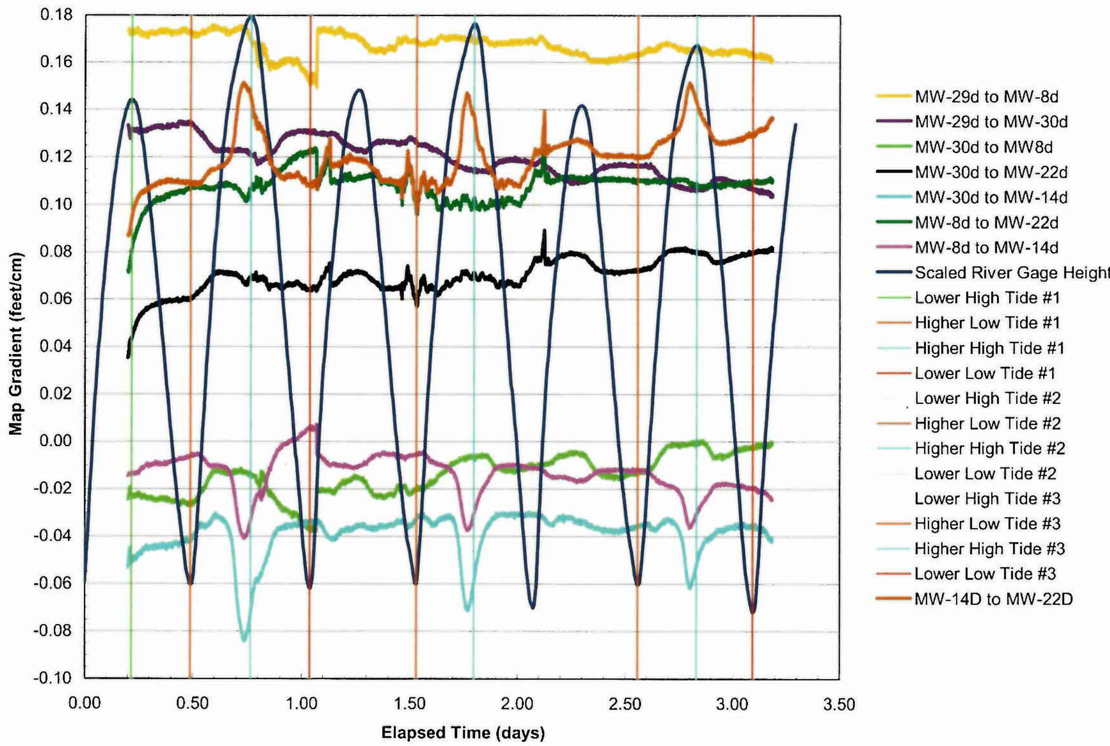


Figure C-65. Map gradients for ground water levels between D-zone wells along the northern boundary during the June 2003 tidal study. Negative gradients indicate flow toward the first well listed in the pair.

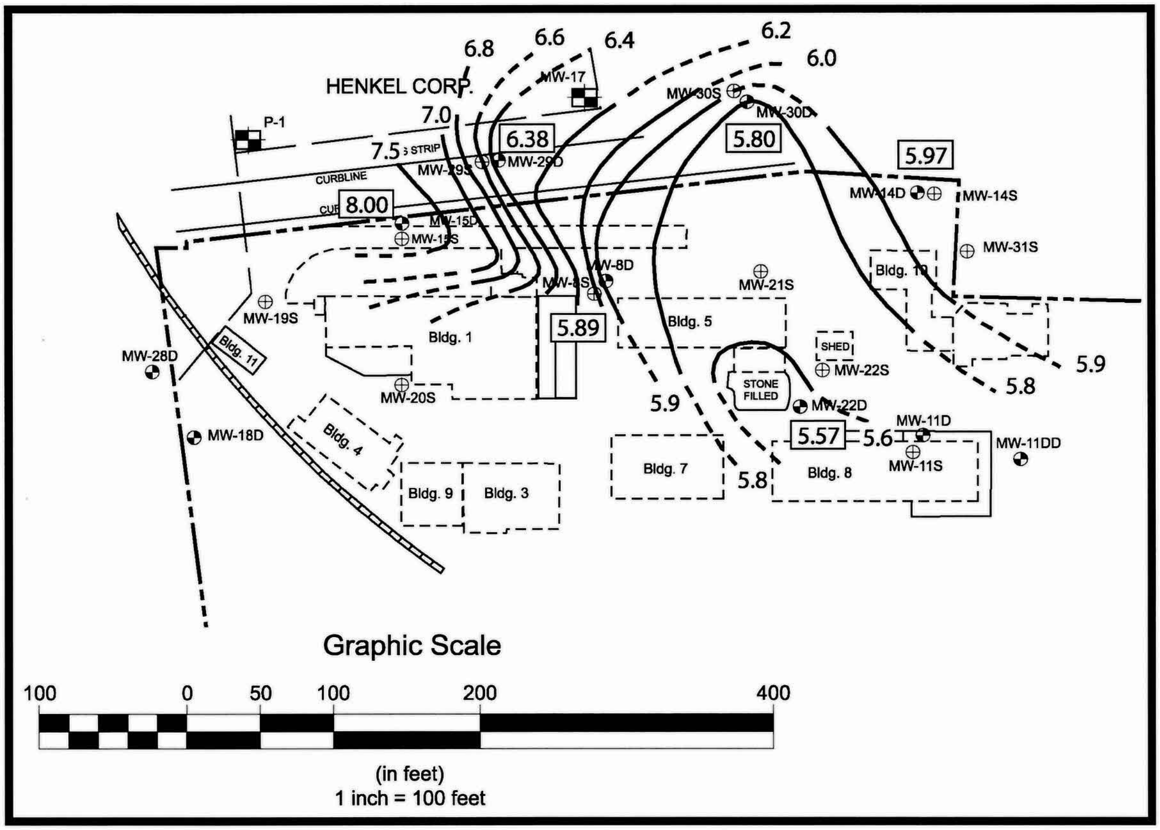


Figure C-66. Piezometric surface map for the deep, D-well zone along the northern boundary, June 13, 2003 10:12 AM. Elapsed time is 0.22083 days, approximate time of the first lower high tide.

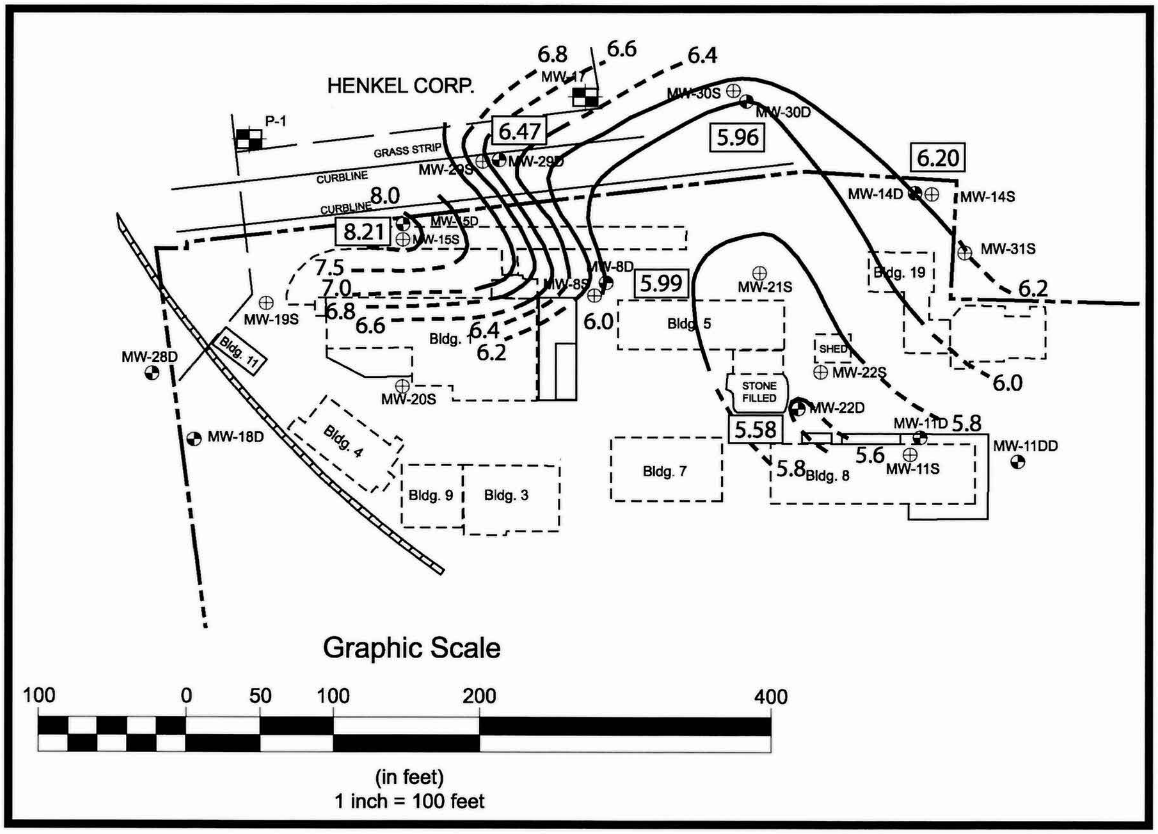


Figure C-67. Piezometric surface map for the deep, D-well zone along the northern boundary, June 14, 2003 11:25 PM. Elapsed time is 1.76736 days, approximate time of the second higher high tide.

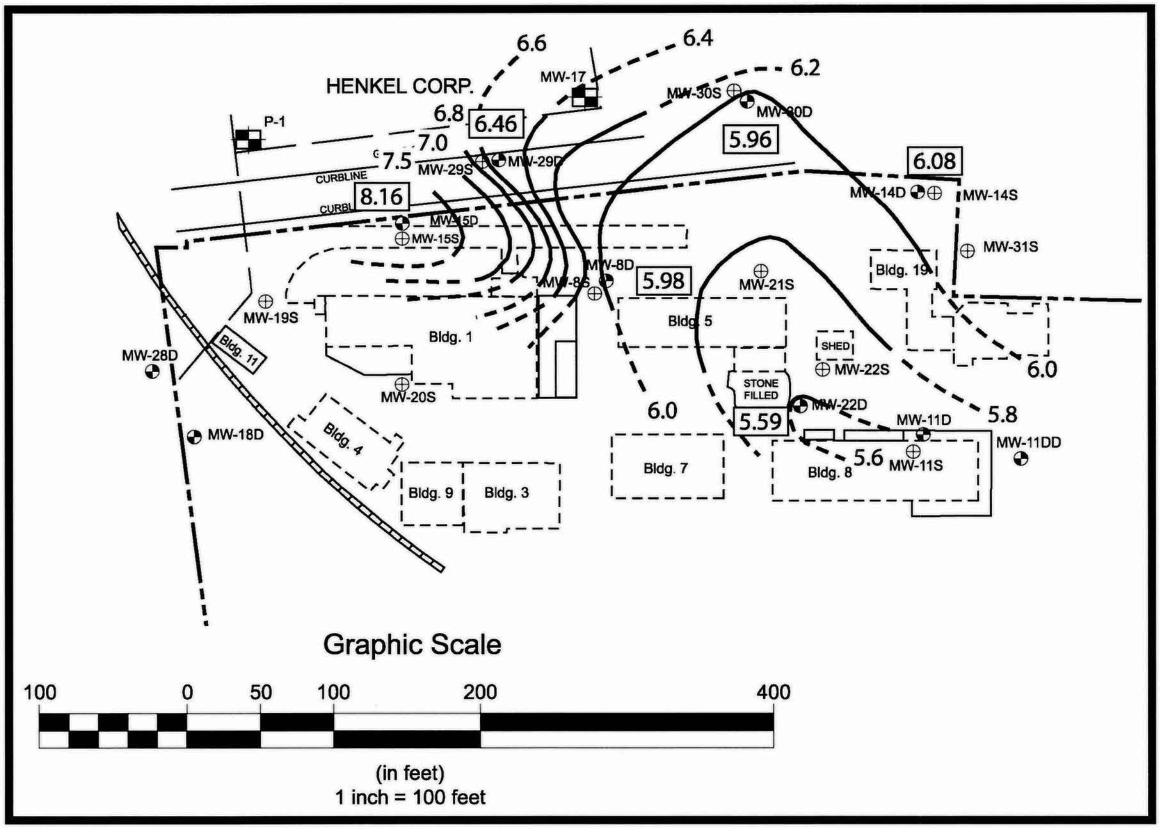


Figure C-68. Piezometric surface map for the deep, D-well zone along the northern boundary, June 15, 2003 1:24 AM. Elapsed time is 1.85000 days, an intermediate time between the second higher high tide and second lower low tide.

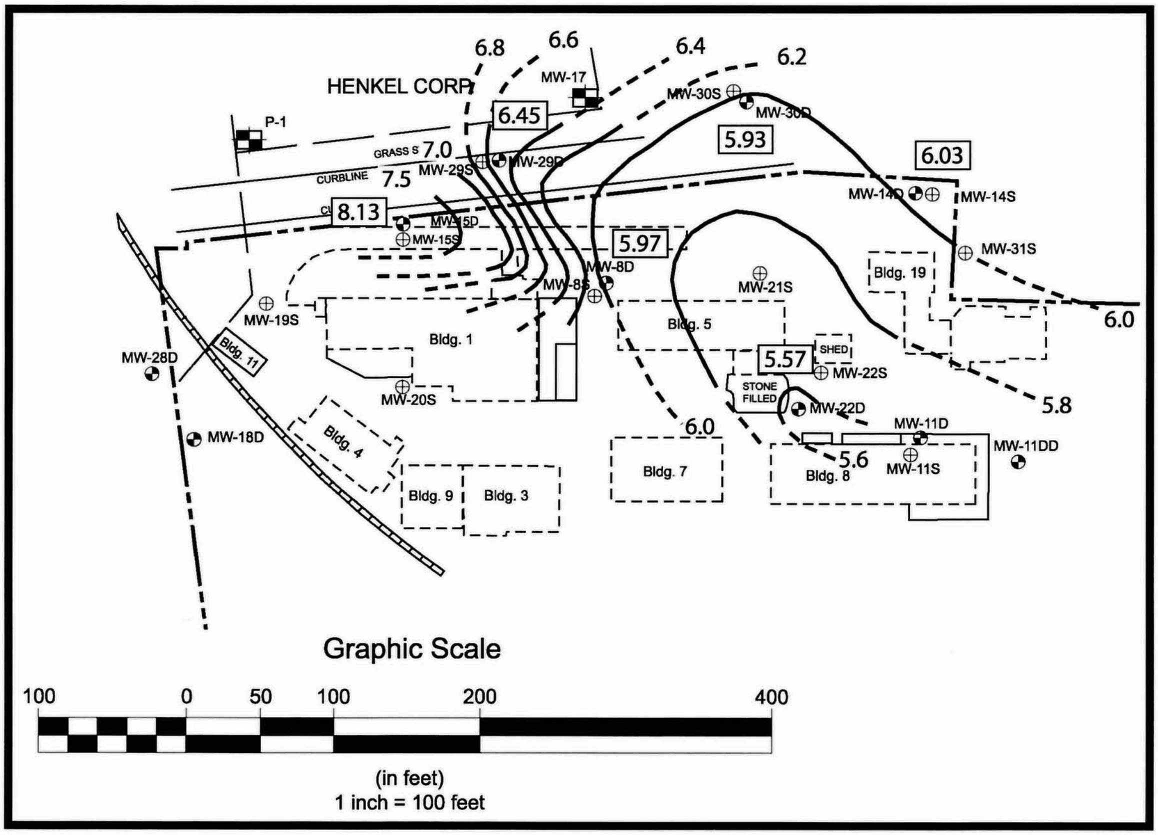


Figure C-69. Piezometric surface map for the deep, D-well zone along the northern boundary, June 15, 2003 8:32 AM. Elapsed time is 2.14722 days, approximate time of the second lower low tide.

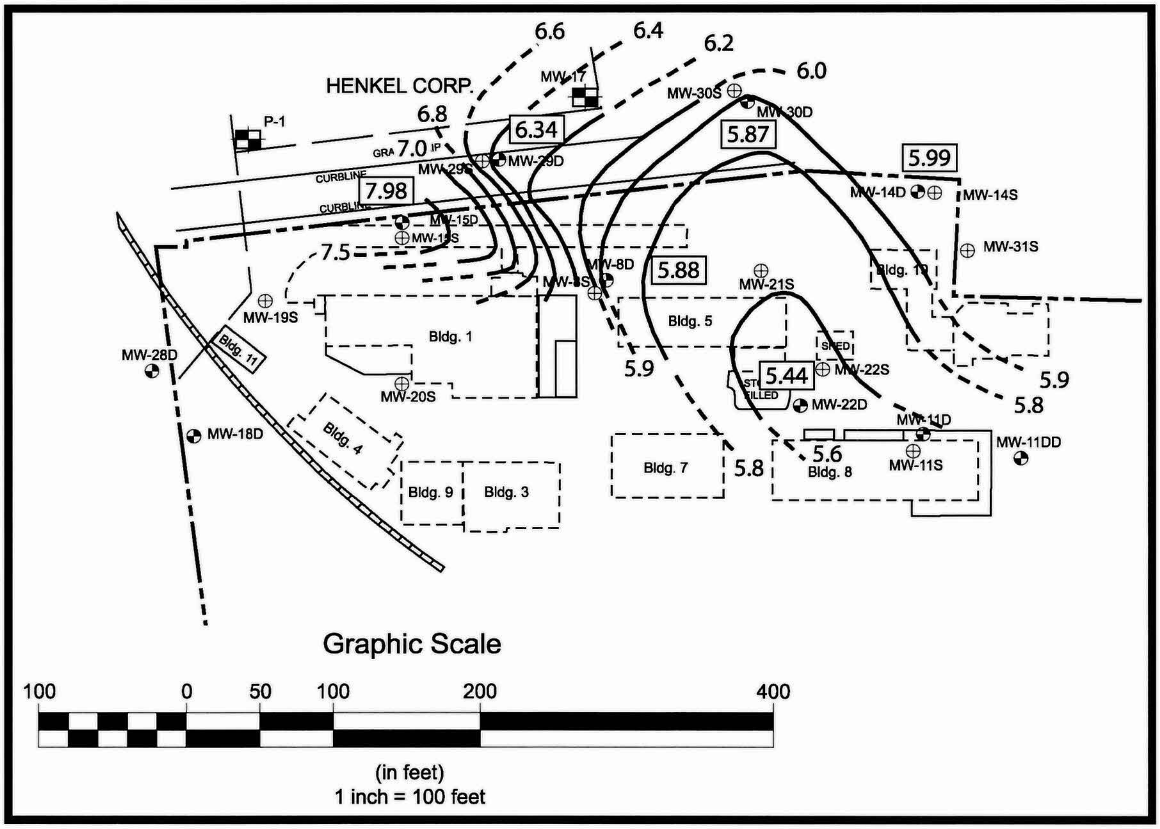


Figure C-70. Piezometric surface map for the deep, D-well zone along the northern boundary, June 16, 2003 7:18 AM. Elapsed time is 3.09583 days, approximate time of the third lower low tide.

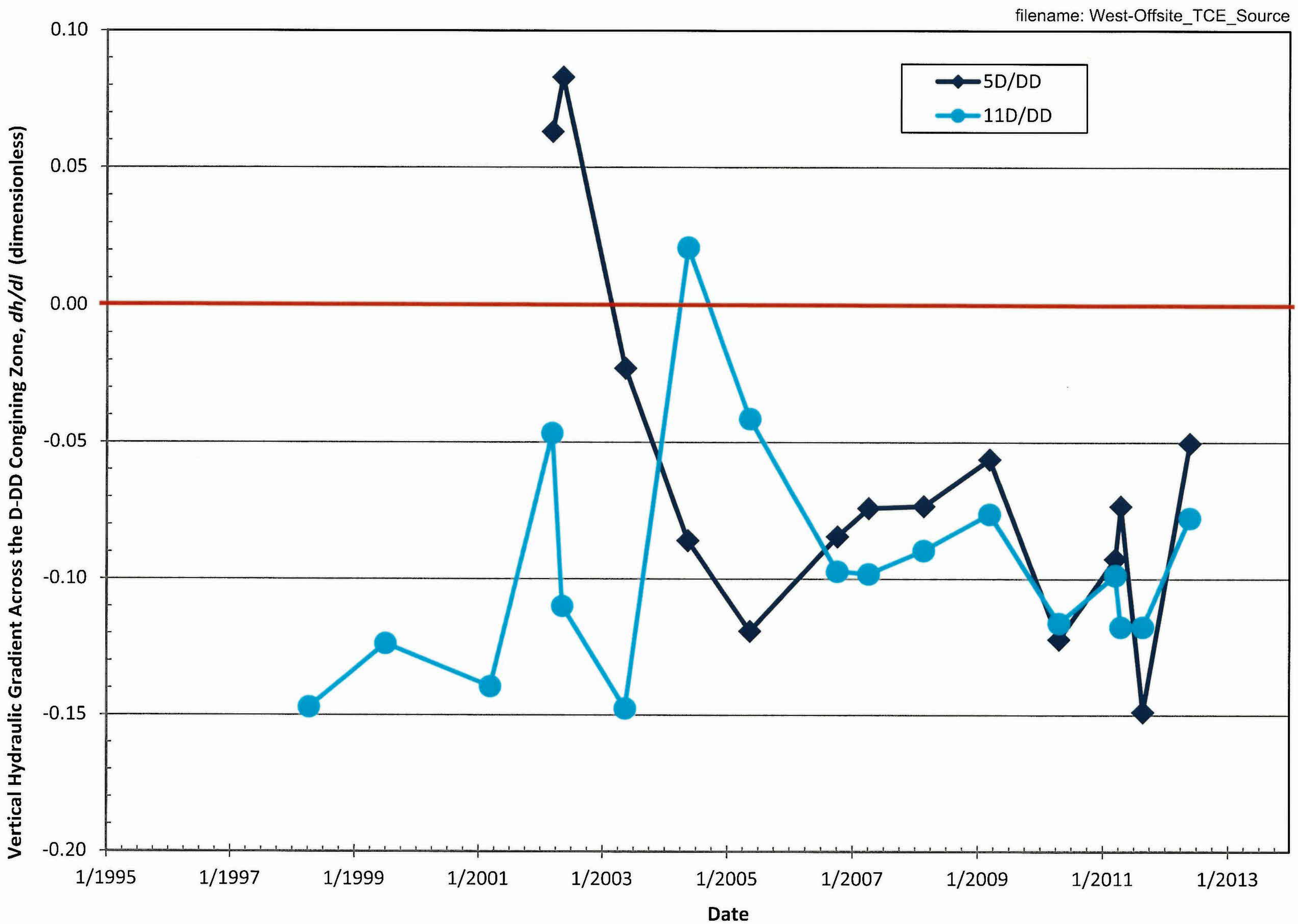


Figure C-71. Historical hydraulic gradients across the D-DD confining zone.

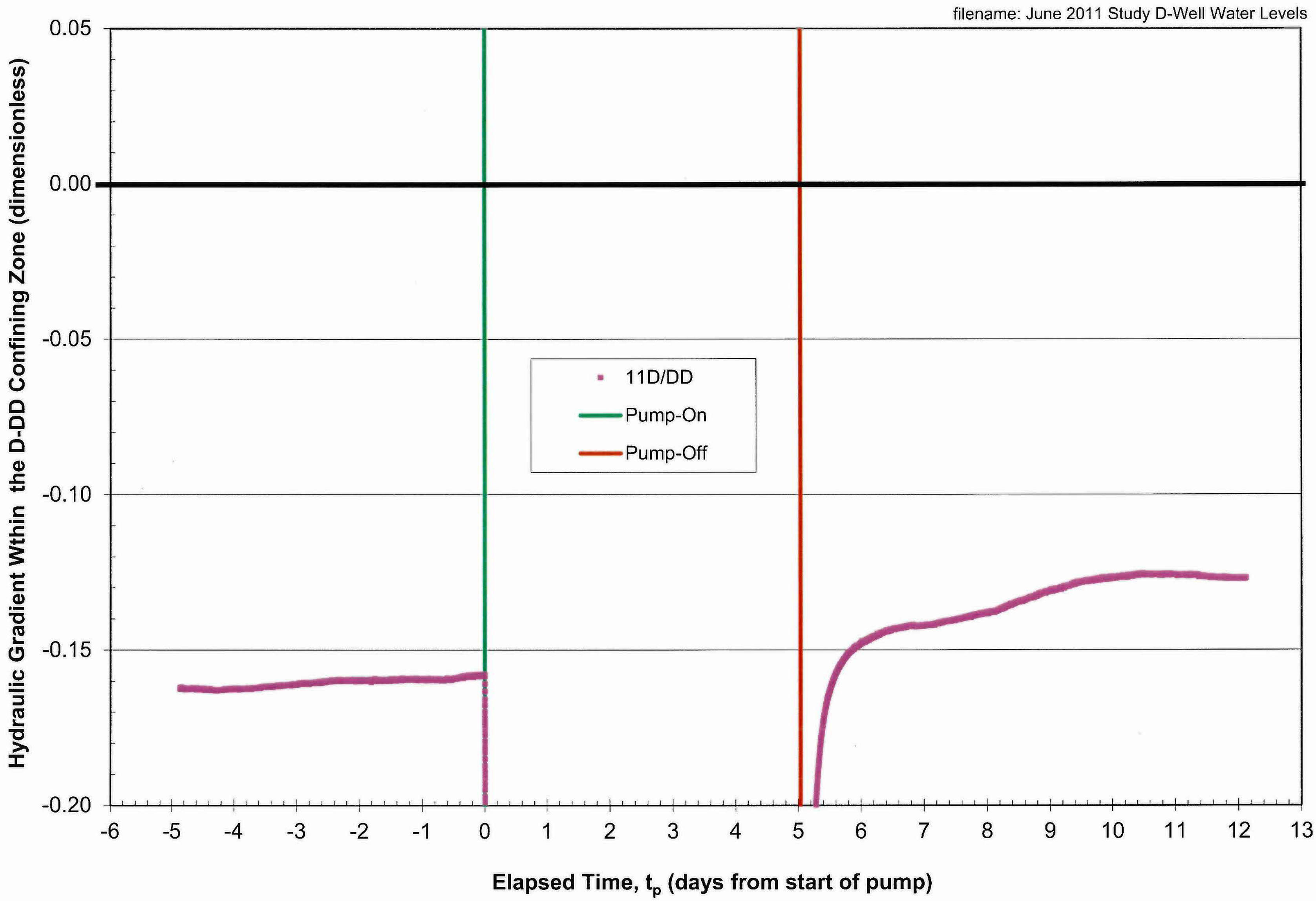


Figure C-72. Hydraulic gradient across the D-DD confining zone during the June 2011 Study.

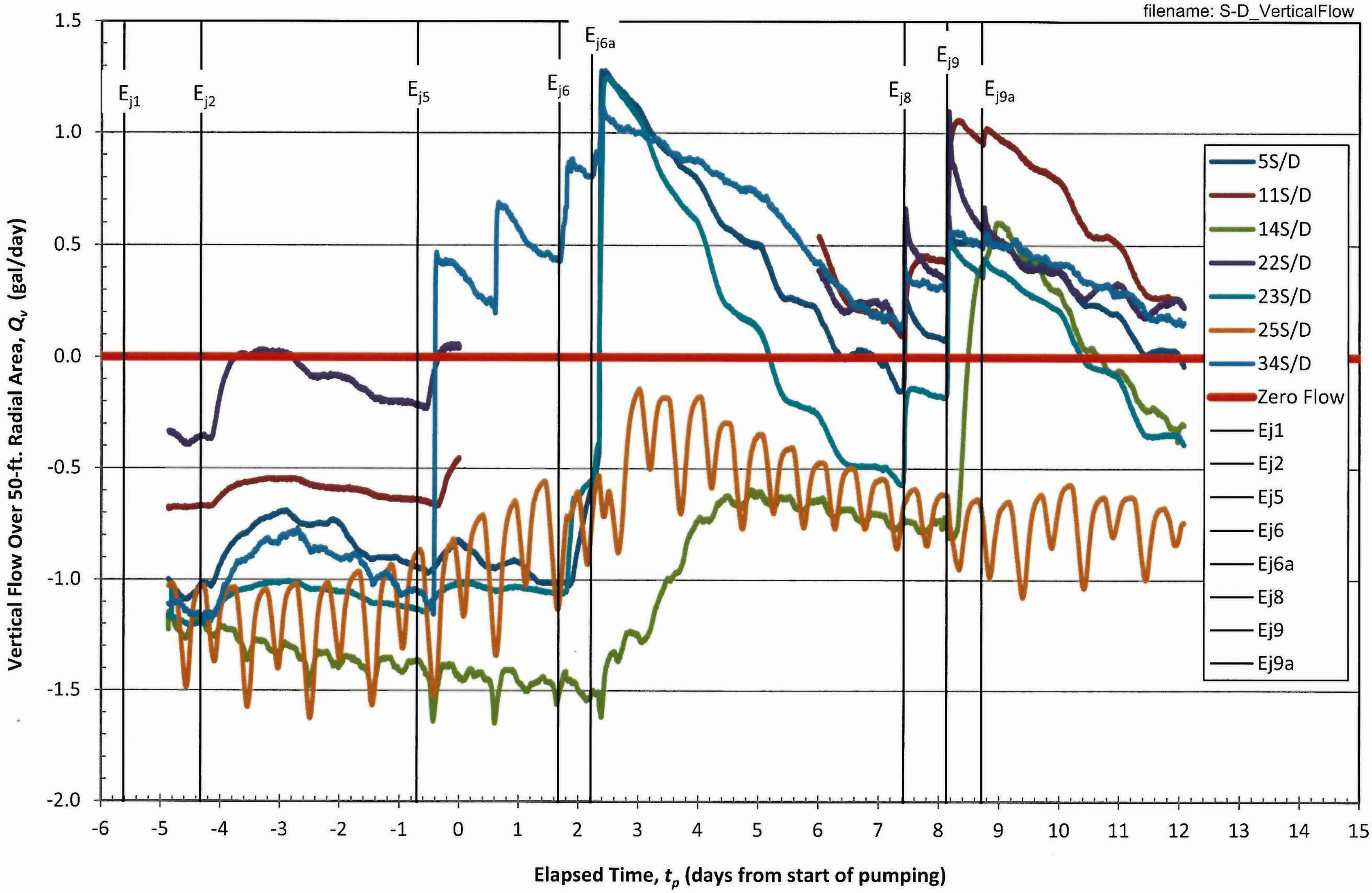


Figure C-73. Vertical groundwater flow rates across the S-D confining zone during the June 2011 study. Flow units are gal/day over a radial area of 50 feet radius. Negative values indicate upward flow. See text for discussion.

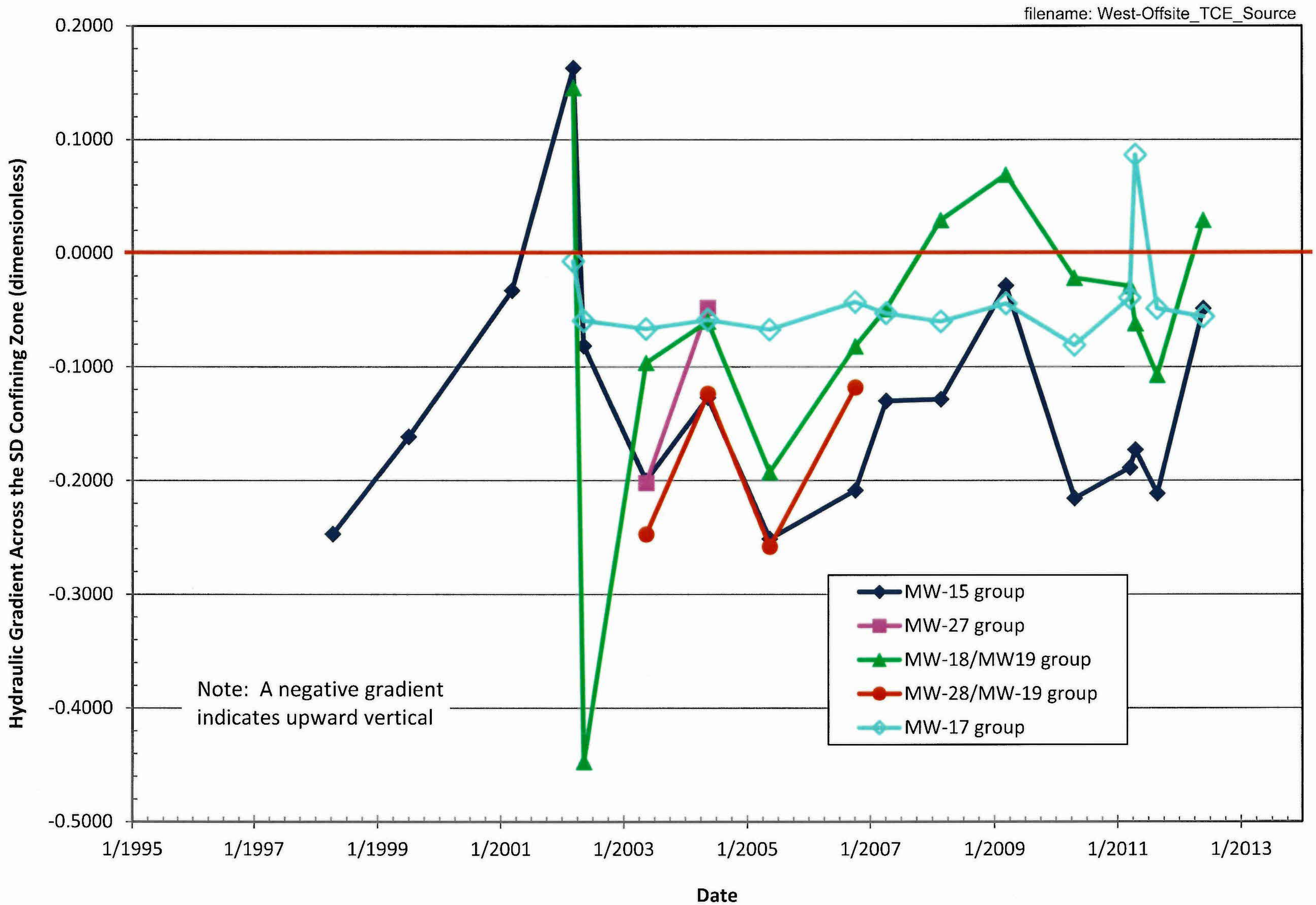


Figure C-74. Hydraulic gradients across the S-D confining zone for wells along the western site margin.

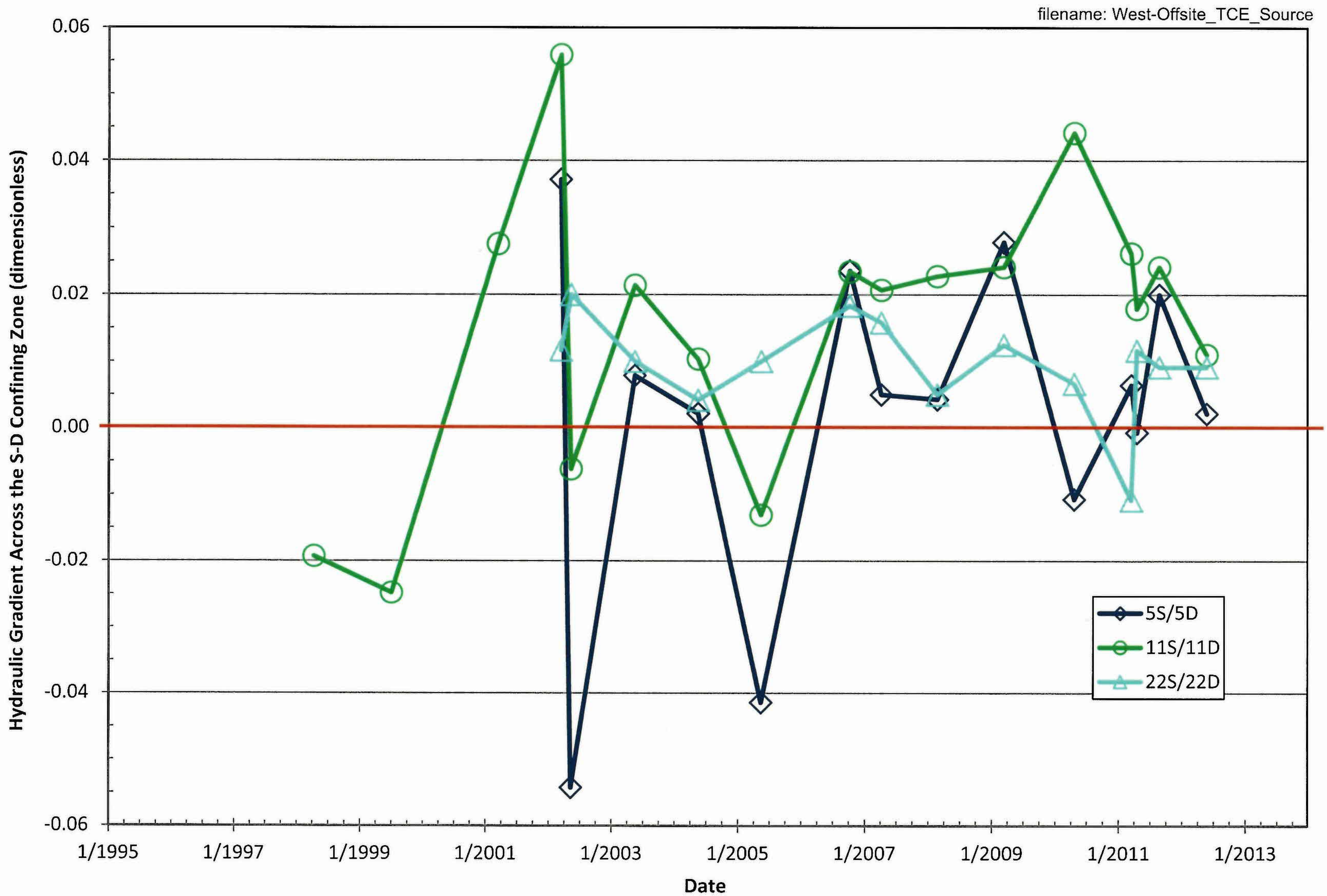


Figure C-75. Hydraulic gradients across the S-D confining zone for near the center of the western site.

Unit Description		Storativity [1]	Hydraulic Conductivity (ft/day) [2]	Method or Basis for Computing Median Parameter Values	References
Fractured Bedrock	Nonporous: top 30 – 170 m	0.0002	0.91	Aquifer tests of 32 industrial/municipal wells; most intersect linear fracture zones by design or chance	3,8,16,17,20,21
	top 10 – 100 m	-----	0.57	Specific capacity of 250 wells, adjusted to small drawdown	11
	Porous top 30 – 150 m	0.0003	4.68	Aquifer tests of 52 industrial/municipal wells	2,4,5,9,10,16,18,22,23,14
	top 10 – 200 m		0.312	Specific capacity of 401 wells, as reported by drillers	
Stratified Drift	Coarse-grained (sand and gravel, ice-contact deposit or outwash)	------	170	Aquifer tests or specific capacities adjusted for partial penetration for 157 screened wells, median aquifer thickness 17 m	7,12,13,19
		0.36	------	25 undisturbed samples	1,11
	Fine-grained (fine sand, silt, and clay, marine or lake-bottom)	0.29	0.142	6 undisturbed samples, oriented vertically, lake silts	11
			0.00057	6 undisturbed samples, marine silty clays	14
Till	Loose upper till	0.28	2.66	10 undisturbed samples	1,6,11
	Compact, lower till	0.04	0.00567	4 undisturbed samples (vertical)	11
	Till, not subdivided	-----	0.935	Slug tests of 28 wells	6

1. Specific yield for unconsolidated deposits.
2. For well tests, transmissivity divided by distance penetrated into hydrostratigraphic unit; the resulting values describe an isotropic homogeneous medium hydraulically equivalent to the real unit, which is heterogeneous and which in bedrock may be strongly anisotropic, with flow limited to fractures or fracture zones that intersect a small fraction of borehole length.

References

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2. Callan (1978)
3. Carr (1967)
4. Francis (1981)
5. Hennigar (1972)
6. Huntley and Black (1979)
7. Lang et al. (1960)
8. Lin (1975)
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10. Randall (1964)
11. Randall et al. (1964)
12. Rosenshein et al. (1968)
13. Ryder et al. (1970)
14. Ryder et al. (1981)
15. Sammel et al. (1966)
16. Trescott (1968)
17. Trescott (1969)
18. Vaughan and Somers (1980)
19. Wilson et al. (1974)
20. BCI Geonetics, unpub.
21. Dunn Geoscience Corp., unpub.
22. PEI Water Res. sect. unpub.
23. U.S. Geological Survey, unpub

Table CT-1. Median hydraulic properties of glacial deposits from the Northeastern Appalachians Hydrogeologic Region. (after Randall et al. 1988).

Shallow Zone Well Number	Hydraulic Conductivity (ft/day)	Deep Zone Well Number	Hydraulic Conductivity (ft/day)	dd-Zone Well Number	Hydraulic Conductivity (ft/day)
MW-10S	76.6	MW-6D	37.4	MW-11DD	0.0000216
MW-13S	10.9	MW-15D	13.2		
MW-7S(*)	7.44	MW-16D	0.883		
MW-11S	6.44	MW-14D	0.717		
MW-15S	3.60	MW-8D	0.320		
MW-9S	3.10	MW-5D	0.124		
MW-8S	1.35	MW-9D	0.0730		
MW-12S	0.179	MW-13D	0.0477		
MW-5S	0.113	MW-12D	0.0350		
MW-14S	0.0533	MW-11D	0.0251		
MW-4	0.0130	MW-10D	0.0120		

Note: * - Sufficient aquitard (meadowmat) thickness may be absent at the location of well MW-7S due to its proximity to the shallow area of the single unit delta complex. Therefore, MW-7S may not be representative of "shallow" groundwater on the site.

Table CT-2. Hydraulic conductivity (K) measurements from Arsynco site wells. Results are listed in order of decreasing K with columns organized by hydrostratigraphic zone. (data from JM Sorge, Inc. 1997)

Feb-March 2002 Date	Newark Precipitation (inches)	Teterboro Precipitation (inches)	May 2002 Date	Newark Precipitation (inches)	Teterboro Precipitation (inches)	May 2003 Date	Newark Precipitation (inches)	Teterboro Precipitation (inches)
18	0.00	0.00	17	0.03		5	0.00	
19	0.00	0.00	18	1.15		6	0.03	0.04
20	0.00	0.00	19	0.38	0.00	7	0.00	0.00
21	0.05		20	0.00	0.00	8	0.37	0.38
22	0.00	0.00	21	0.00	0.00	9	0.04	0.05
23	0.00	0.00	22	0.03	0.00	10	0.05	0.00
24	0.00	0.00	23	0.00	0.00	11	0.01	0.00
25	0.00	0.00	24	0.00	0.00	12	0.04	0.04
26	0.00	0.00	25	0.03	0.00	13	0.00	0.01
27	0.09		26	0.00	0.00	14	0.00	0.00
28	0.03		27	0.00	0.00	15	0.00	0.00
1	0.00	0.00	28	0.00		16	0.00	
2	0.00	0.00	29	0.00	0.00	17	0.00	0.01
3	0.99		30	0.00	0.00	18	0.00	0.00
Cumulative Precipitation (inches)	1.16	0.00		1.62	0.00		0.54	0.53

Table CT-3. Precipitation records at Teterboro Airport and Newark International Airport for two weeks prior the three most recent rounds of water level measurements used to prepare ground water maps.

Date	Time Range	Stage of Moon	Location in Daily Tide Cycle
2/1/1995	7:45 – 8:15 AM	1½ days after new moon	~2 hours before higher high tide
4/10/1996	8:30 – 9:30 AM *	½ day before first quarter	~ 1½ hours after higher low tide
1/14/1997	8:30 – 9:30 AM	1½ days before first quarter	~ 1½ hours after higher low tide
4/28/1998	7:30 – 9:30 AM **	1½ days after new moon	~2 hours before lower high tide
8/7/1998	11:36 AM – 12:12 PM	¼ day before full moon	~ 4 hours after lower high tide
7/6/1999	7:30 – 8:30 AM	½ day before last quarter	at lower low tide
3/15/2001	9:00 – 9:30 AM	1½ days before last quarter	~ 1½ hours after lower low tide
3/4/2002	7:00 – 8:00 AM	1½ days before last quarter	~ 1 hour after lower low tide
5/31/2002	11:59 AM – 12:29 PM	1¼ days before last quarter	at or just before lower high tide
5/19/2003	8:14 – 9:26 AM	3½ days after full moon	~ 2½ hours after lower low tide

Notes: * Time range estimated based on start of pre-purge for first well sample and average length of time required to collect water levels.

** Time estimated based on times of other sampling dates.

Table CT-4. Historical dates and times of ground water flow maps at the Arsynco site and their estimated temporal location within the tidal cycle. (Sources: NOAA 1995; International Marine 1995; 1997; 1998; 1999; 2001, 2002, 2003)

Sequential Peak Number	Time of Peak in MW-8D (days)[1]	Time of Peak in MW-10D (days)[1]	Time of Peak in MW-12D (days)[1]	Difference in Timing of Peak (MW-10-MW12) (days)	Difference in Timing of Peak (MW-10-MW12) (minutes)
1	0.9219 [2]	0.9278	0.9524	-0.0246	- 35
2		1.4967	1.4889	-0.0078	- 11
3		1.9955	1.9993	-0.0038	- 5.5
4	2.6927 [2]	2.6486	2.5045	0.1441	208
5		3.0163	3.0201	-0.0038	- 5.5
6		3.5788	3.5306	0.0482	69
7		4.0736	4.0774	-0.0004	- 0.6
8	4.6250 [2]	4.6153	4.5722	0.0431	62
9	5.1458	5.1257	5.1295	-0.0038	- 5.5
10	5.6198	5.6257	5.6347	-0.0090	- 13
11		6.1517	6.1556	-0.0039	- 5.6

Notes: 1. Day zero was defined as February 16, 1995 12:00 AM.
2. Timing of peak not definitive.

Table CT-5 Timing of tidal high-water levels in the D-wells during the February 1995 tidal study.

Peak or Trough Description	Time of Occurrence (days)[1]	Gage Height (feet)[2]	Tidal Range (feet)
Lower High Tide cycle #1	0.2167	3.45	
Higher Low Tide	0.4896 [3]	-3.52	6.97
Higher High Tide	0.7646 [3]	4.65	8.17
Lower Low Tide	1.0375	-5.58	10.23
Lower High Tide cycle #2	1.2625	3.59	9.17
Higher Low Tide	1.5292	-3.52	7.11
Higher High Tide	1.7979 [3]	4.55	8.07
Lower Low Tide	2.0729 [3]	-3.85	8.40
Lower High Tide cycle #3	2.2958 [4]	3.36	7.21
Higher Low Tide	2.5583	-3.53	6.89
Higher High Tide	2.8313 [3]	4.24	7.77
Lower Low Tide	3.0958	-3.93	8.17

Notes:
1. Time expressed as elapsed time referenced to zero days at 6/13/2003 05:00:00.
2. Unscaled gage height.
3. Represents an average of two times with equal gage height.
4. Center time of three times with equal gage height.

Table CT-6. Timing of peaks and troughs recorded at the USGS Hackensack River Gaging Station located at Hackensack, NJ.

	Regional Data			Teterboro Airport 2003	
Time Frame	average (inches)	standard deviation, s (inches)	n	Precipitation (inches)	Difference from regional average [1]
Annual	46.94	8.43	452		
Cumulative through May	18.61	4.84	452	17.44	-0.24s
Cumulative through June	22.27	5.44	452	26.90	+0.85s
June	3.69	1.99	563	9.46	+2.90s
Prior to June13				5.66	+0.99s
Through End of Study (June 16)				6.94	+1.63s

Notes: 1. Differences expressed in terms of multiples of the corresponding regional standard deviation.

Table CT-7. Comparison of precipitation at Teterboro Airport for 2003 and regional average precipitation values.

Date	4/1/1998	8/7/1998	7/1/1999	3/1/2001	3/4/2002	5/31/2002	5/19/2003
Average Difference #1	-0.30	-0.41	-0.38	0.31	0.99	-0.20	0.03
Average Difference #2					0.91	-0.43	-0.20
Average Difference #3							-0.42

Table CT-8. Average vertical differences in head between shallow, S-wells, and the deep, D-wells for all available dates where ground water levels were obtained. The different averages are based on the installation of new wells, as explained in the text. Head differences are expressed in feet.

Date / Cluster	4/1/1998	8/7/1998	7/1/1999	3/1/2001	3/4/2002	5/31/2002	5/19/2003
MW-5					0.85	0.12	-0.31
MW-11	-3.09	-3.09	-2.60	-2.93	-0.98	-2.31	-3.10

Table CT-9. Average vertical differences in head between deep, D-wells, and the double-deep, DD-wells for all available dates where ground water levels were obtained. Head differences are expressed in feet.

REFERENCES

NCDC. 2003. National Climate Data Center. Ashville, NC. www.ncdc.noaa.gov

Date \Well Group	15S/D	27S/D	19S/18D	19S/28D	17S/D
4/15/1998	-0.2471				
7/7/1999	-0.1614				
3/15/2001	-0.0329				
3/15/2002	**0.1629**		**0.1455**		-0.0071
5/15/2002	-0.0814		-0.4473		-0.0593
5/19/2003	-0.2000	-0.2020	-0.0964	-0.2473	-0.0664
5/19/2004	-0.1271	-0.0480	-0.0600	-0.1236	-0.0586
5/18/2005	-0.2514		-0.1927	-0.2582	-0.0671
10/10/2006	-0.2086		-0.0818	-0.1182	-0.0429
4/11/2007	-0.1300		-0.0491		-0.0529
2/26/2008	-0.1286		**0.0291**		-0.0600
3/16/2009	-0.0286		**0.0691**		-0.0443
4/26/2010	-0.2157		-0.0218		-0.0807
3/21/2011	-0.1886		-0.0291		-0.0393
4/22/2011	-0.1729		-0.0618		**0.0864**
8/29/2011	-0.2114		-0.1073		-0.0486
5/29/2012	-0.0486		**0.0291**		-0.0557
Average Hydraulic Gradients:	-0.1336	-0.1250	-0.0625	-0.1868	-0.0426
Specific Discharge for Vertical Groundwater Flow, Q_v' ($ft^3/ft^2/day$)					
Maximum:	-3.81E-04	-3.56E-04	-1.78E-04	-5.32E-04	-1.21E-04
Minimum:	-3.81E-06	-3.56E-06	-1.78E-06	-5.32E-06	-1.21E-06
Likely:	-3.81E-05	-3.56E-05	-1.78E-05	-5.32E-05	-1.21E-05
Discharge for Vertical Groundwater Flow Around a Radial Distance of 50 ft., Q_v (gal/day)					
Maximum:	-22.37	-20.93	-10.46	-31.28	-7.13
Minimum:	-0.22	-0.21	-0.10	-0.31	-0.07
Likely:	-2.24	-2.09	-1.05	-3.13	-0.71

Table CT-10. Historical data for vertical groundwater flow across the S-D confining zone for well groups along the western margin of the site. Negative values indicate upward vertical flow. Values in bold text indicate downward vertical flow.

Date \Well Group	5S/D	11S/D	22S/D
4/15/1998		-0.0193	
7/7/1999		-0.0248	
3/15/2001		**0.0276**	
3/15/2002	**0.0371**	**0.0559**	**0.0117**
5/15/2002	-0.0543	-0.0062	**0.0200**
5/19/2003	**0.0079**	**0.0214**	**0.0100**
5/19/2004	**0.0021**	**0.0103**	**0.0042**
5/18/2005	-0.0414	-0.0131	**0.0100**
10/10/2006	**0.0236**	**0.0234**	**0.0183**
4/11/2007	**0.0050**	**0.0207**	**0.0158**
2/26/2008	**0.0043**	**0.0228**	**0.0050**
3/16/2009	**0.0279**	**0.0241**	**0.0125**
4/26/2010	-0.0107	**0.0441**	**0.0067**
3/21/2011	**0.0064**	**0.0262**	-0.0108
4/22/2011	-0.0007	**0.0179**	**0.0117**
8/29/2011	**0.0200**	**0.0241**	**0.0092**
5/29/2012	**0.0021**	**0.0110**	**0.0092**
Average Hydraulic Gradients:	0.0021	0.0157	0.0095
Average Specific Discharge for Vertical Groundwater Flow, Q_v' ($ft^3/ft^2/day$)			
Maximum:	5.96E-06	4.46E-05	2.71E-05
Minimum:	5.96E-08	4.46E-07	2.71E-07
Likely:	5.96E-07	4.46E-06	2.71E-06
Average Discharge for Vertical Groundwater Flow Around a Radial Distance of 50 ft., Q_v (gal/day)			
Maximum:	0.350	2.622	1.595
Minimum:	0.004	0.026	0.016
Likely:	0.035	0.262	0.159

Table CT-11. Historical data for vertical groundwater flow across the S-D confining zone for well groups near the center of the site. Negative values indicate upward vertical flow. Values in bold text indicate downward vertical flow.

Date \Well Group	5D/DD	11D/DD
4/15/1998		-0.1471
7/7/1999		-0.1238
3/15/2001		-0.1395
3/15/2002	**0.0630**	-0.0467
5/15/2002	**0.0830**	-0.1100
5/19/2003	-0.0230	-0.1476
5/19/2004	-0.0859	**0.0210**
5/18/2005	-0.1193	-0.0414
10/10/2006	-0.0844	-0.0971
4/11/2007	-0.0741	-0.0981
2/26/2008	-0.0733	-0.0895
3/16/2009	-0.0563	-0.0762
4/26/2010	-0.1222	-0.1162
3/21/2011	-0.0926	-0.0986
4/22/2011	-0.0733	-0.1176
8/29/2011	-0.1489	-0.1176
5/29/2012	-0.0504	-0.0776
Average Hydraulic Gradients:	-0.0613	-0.0955
Average Specific Discharge for Vertical Groundwater Flow, Q_v' ($ft^3/ft^2/day$)		
Maximum:	-1.75E-04	4.46E-05
Minimum:	-1.75E-06	4.46E-07
Likely:	-1.75E-05	4.46E-06
Average Discharge for Vertical Groundwater Flow Around a Radial Distance of 50 ft., Q_v (gal/day)		
Maximum:	-1.60E+01	2.62E+00
Minimum:	-1.60E-01	2.62E-02
Likely:	-1.60E+00	2.62E-01

Table CT-12. Historical data for vertical groundwater flow across the D-DD confining zone. Negative values indicate upward vertical flow. Values in bold text indicate downward vertical flow.